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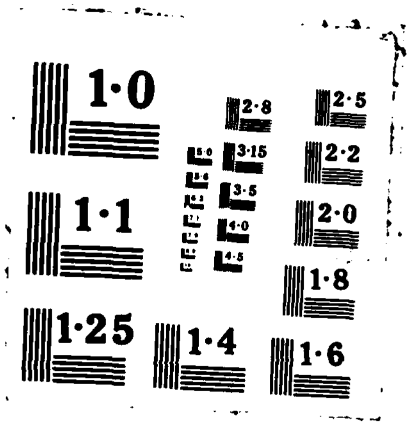
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THE IMPACT OF VERTICAL AXIS CHARACTERISTICS ON HELICOPTER HANDLING QUALITIES

by

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National Aeronautical Establishment

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THE IMPACT OF VERTICAL AXIS CHARACTERISTICS
ON HELICOPTER HANDLING QUALITIES

EFFET DES CARACTÉRISTIQUES D'AXE VERTICAL
SUR LA MANIABILITÉ DES HÉLICOPTÈRES

by/par

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SUMMARY

The results of two in-flight simulation programs on the impact of vertical axis characteristics on rotorcraft handling qualities are presented. The parameters investigated ~~in these studies~~ were heave damping, thrust to weight ratio, and various dynamic response characteristics of the combined engine, governor and rotor system. Flight tasks included hover, hover manoeuvring and nap of the earth flight. Evaluation of 11 configurations where heave damping and thrust to weight ratio values were varied provides the basis to suggest that the amount of heave damping represented by $Z_w = -0.20 \text{ sec}^{-1}$ and a thrust to weight ratio of 1.08 are the boundary values for Level 1 helicopter handling qualities. These results are compared with other relevant work on the topic.

Stabilization and control of engine torque was found to be a major source of pilot workload for models with higher order engine-rotor system response characteristics of a 3 db resonant peak in the transfer function between collective and engine torque, is postulated as an upper limit for Level 1 handling qualities. The benefit of displacing this peak to higher frequencies, corresponding to separating the resonance from the typical pilot's bandwidth, is suggested. The evaluation results tend to discount the use of a vertical velocity shaping parameter for definition of Level 1 attributes when thrust to weight ratio is a dominant factor and suggest that the impact of such dynamic characteristics is highly sensitive to pilot technique and adaptability.

Note: This report makes reference to a proposed revision to MIL-H-8501A (Reference 5) which was published December 1985. Subsequent editions of the proposed revision incorporate many of the conclusions detailed in this report.

RÉSUMÉ

On présente les résultats de deux programmes de simulation en vol visant à déterminer l'effet des caractéristiques d'axe vertical sur la maniabilité des giravions. Les paramètres étudiés étaient l'amortissement de pilonnement, le rapport de la poussée à la masse et différentes caractéristiques de réponse dynamique de l'ensemble moteur-régulateur-rotor. Les activités de vol comprenaient le vol stationnaire, les manoeuvres en vol stationnaire et le vol en rase-mottes. L'évaluation de 11 configurations dans lesquelles on faisait varier l'amortissement de pilonnement et le rapport de la poussée à la masse donne des résultats qui permettent de croire qu'un degré d'amortissement de pilonnement représenté par $Zw = -0{,}20\ s^{-1}$ et un rapport de la poussée à la masse de 1,08 sont les valeurs limites pour le niveau 1 de maniabilité des hélicoptères. Les résultats sont comparés avec d'autres travaux pertinents sur le sujet.

On a constaté que la stabilisation et le contrôle du couple moteur constituent une partie importante de la charge de travail des pilotes sur les modèles ayant des caractéristiques de réponse de l'ensemble moteur-rotor de niveau supérieur, et on propose une crête de résonnance de 3 db dans la fonction de transfert entre la commande de pas général et le couple moteur comme limite supérieure pour la maniabilité de niveau 1. On suggère de profiter de l'avantage résultant du déplacement de cette crête vers les plus hautes fréquences, ce qui correspond à séparer la fréquence de résonnance de la plage de fréquences propre au pilote. Les résultats de l'évaluation ne semblent pas tenir compte de l'utilisation d'un paramètre de mise en forme de la vitesse verticale pour la définition des attributs du niveau 1 lorsque le rapport de la poussée à la masse est un facteur dominant et portent à croire que les effets de ces caractéristiques dynamiques dépendent grandement de la technique et de l'adaptabilité du pilote.

Note: Le présent rapport fait référence à une version révisée proposée du document MIL-H-8501A (référence 5) qui a été publié en décembre 1985. Les éditions subséquentes de la version révisée proposée contiennent un grand nombre de conclusions décrites dans le présent rapport.

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1.0 INTRODUCTION

Vertical axis handling qualities have been the subject of numerous research programs. As early as 1962, in response to a VTOL handling qualities specification program, fixed-base simulations of VTOL tasks were carried out to determine handling qualities requirements for height control (Gerdes and Weick, 1962). The results of this initial study suggested an optimum height control sensitivity range of .21 - .37 g in $^{-1}$ and a minimum thrust to weight ratio (T/W) of 1.20. This work also pointed out the importance of the aircraft heave damping derivative (Zw) and ground effect.

Further in-flight simulation by Kelly et al (1967) utilizing the NASA CH-47 showed that the T/W limit is strongly dependent upon the evaluation task. For a takeoff-circuit-landing task the minimum T/W for satisfactory flying qualities was found to be at 1.09 with a minimum climb capability of 600 ft/min. For an approach task alone, however, a minimum T/W of 1.03 could be allowed, provided that the heave damping was greater than that provided by Zw = -0.25 sec^{-1} (a larger absolute value of Zw corresponds to greater heave damping).

Both of these studies indicated the strong coupling effects of collective (or lift control) sensitivity (Z_{δ_C}), heave damping derivative, and overall control authority (T/W). They also showed, not suprisingly, that task selection, and the inherent performance requirements for that task, can significantly affect any resulting parameter limits.

In 1979 Hoh and Ashkenas summarized the available data base for VTOL handling qualities and the data base deficiencies at that time. Some of the issues raised in that document included requirements to:

1) Establish the effects of external disturbances in longitudinal and lateral axes on vertical axis damping requirements, possibly by increasing longitudinal and lateral stability levels;

2) Isolate the effects of vertical axis damping from steady state climb rate due to collective input, $((w/\delta c)ss)$;

and,

3) Investigate the effect of nonlinear engine response on handling qualities.

Renewed emphasis on vertical axis handling qualities, partially in response to a U.S. Army program to update MIL-H-8501A, Helicopter Flying and Ground Handling Qualities (References 4 & 5), provides a strong impetus to further investigate the issues raised in these earlier research programs.

The Flight Research Laboratory of the National Aeronautical Establishment, under the auspices of TTCP (The Technical Cooperation Program) and in close cooperation with Systems Technology Inc. and the U.S. Army, have been performing helicopter handling qualities research to support the ongoing MIL-H-8501A update. The overall thrust of this in-flight simulation program has been to provide validated 'anchor points' corresponding to models used in fixed- and moving-base simulator research. This paper will deal with the segment of this program which has been concerned with the impact of vertical axis characteristics on helicopter handling qualities. The paper will describe two experiments, one dealing with required heave damping levels in the environment of advanced control systems and the second dealing with the issues of thrust to weight ratio limits and the effects of the dynamic response characteristics of the engine, governor and rotor system. The paper will summarize the procedures and results of the first experiment (Reference 6) and will then fully describe the second experiment. These experiments have counterpart programs on both the NASA-Ames VMS (Vertical Motion Simulator) and the NASA-Ames CH-47 variable stability helicopter. The discussion of results of this present research will be made in the context of these other programs.

2.0 EXPERIMENTAL DESIGN

Both experiments to be discussed here were conducted on the NAE Bell 205 Airborne Simulator (Reference 7 and Figure 1). The evaluation pilot station was fitted with conventional controls with the characteristics shown in Table 1. As with all other in-flight simulations at NAE, the safety pilot was responsible for all system monitoring and overall flight safety. All of the evaluation pilots involved in this program had previous handling qualities evaluation experience. A summary of this experience is included as Table 2.

The control systems used in this experiment were all evaluated in an earlier Flight Research program (Reference 8). The three systems used were Attitude Command/Attitude Hold (ACAH), Rate Command/Attitude Hold (RCAH), and Rate Damped (RD) in pitch and roll axes. Each was assigned a Level 1 Cooper Harper Handling Qualities Rating for hover and hover manoeuvring tasks and control sensitivities were optimized by evaluation pilots at the outset of this program. A block diagram of three systems is included as Figure 2 and each control system bandwidth is listed in Table 3. The yaw axis control was Rate Command for all three pitch and roll systems and incorporated turn coordination and heading hold.

The aircraft vertical axis dynamics were varied using one of two different approaches. For the first experiment, which utilized ACAH or RCAH in the pitch and roll axes, the vertical channel modelling was an augmentation of the basic Bell 205 dynamics. This implementation, shown in Figure 3, incorporates an aircraft vertical velocity (w) feedback loop to alter the heave damping of the aircraft. Modelled to first order as:

$$\frac{w(s)}{\delta c(s)} = \frac{Z_{\delta c}}{s - Zw - K_f Z_{\delta c}}$$

the effective Zw derivative can be defined as:

$$Z_w \text{ eff} = Z_w + K_f \cdot Z_{\delta c}$$

The heave damping values evaluated in this first experiment are tabulated in Table 4. Collective sensitivity ($Z\delta_C$) was initially held constant at 0.28 g in^{-1} and was later modified to pilot preference (to be discussed in an upcoming section). The quoted heave damping and sensitivity characteristics were verified by flight recorded step collective response data and by the use of a maximum likelihood parameter estimation package on flight recorded collective frequency sweeps (Reference 9).

The second vertical channel implementation was used in conjunction with the rate damped version of the pitch and roll control system in the second experiment. As depicted in Figure 4, this implementation is a model-following type in which Zw, T/W, engine governor dynamics (ξ and α), rotor inertia (Ir), and collective to engine governor feedforward gain (G2) could be easily varied. Use of this model was always coupled with a pilot adjustable collective sensitivity. The values of Zw, T/W, ξ, α, Ir and G2 used in this experiment are listed in Table 5.

3.0 EXPERIMENT 1 - HEAVE DAMPING EFFECTS

Using RCAH or ACAH control systems in the pitch and roll axes and the heave damping augmentation scheme in the vertical axis, evaluation pilots flew the hover/manoeuvring course depicted in Figure 5 and a nap of the earth (NOE) course. Each of the six configurations (three Zw levels (-.05, -.65 and -1.25) for each of two control systems (ACAH and RCAH)) was flown a minimum of three times before it was rated using the Cooper-Harper scale (Reference 10). Pilot comments regarding system deficiencies, pilot compensation requirements, performance and overall controllability were solicited and used to guide the overall analysis.

Hover course results for RCAH and ACAH control systems, shown in Figures 6 and 7, demonstrate the same major characteristic. The aircraft model with the lowest heave damping (Zw = -0.05 sec^{-1}), was rated as possessing Level 2 flying qualities with a mean rating of 4.0 for all evaluations. The higher heave damping models were all rated as possessing Level 1 handling qualities for the tasks encompassed in the hover/manoeuvring course.

The NOE results, based on flying the aircraft over trees and clearings in a forest while minimizing visual exposure (known as dolphin flying), were marred by variable weather conditions and a poor sampling of configurations. While the Cooper-Harper ratings were far too variable for analysis, pilot comments did provide good insight into the overall situation. For evaluation flights with collective sensitivity held constant at 0.28 g in^{-1}, lower heave damping cases were preferred over those models with higher heave damping values. This phenomenon was attributed to the reduction in steady-state climb rate for a given collective input when heave damping is increased but collective sensitivity is kept constant, as shown in Figure 8. Later NOE evaluations where pilots were allowed to vary collective sensitivity showed that higher heave damping values were preferred when steady state performance was not compromised. This effect corresponds to the collective step responses shown in Figure 9, where the ratio of $Zw/Z_{\delta c}$ is kept constant. In each flight evaluation, the pilot selected $Z_{\delta c}$ value tended toward a constant $Zw/Z_{\delta c}$ ratio. (To ensure that the hover manoeuvring results were not contaminated by the selection of a constant $Z_{\delta c}$ value, some heave damping cases were re-evaluated over the hover manoeuvring course with pilot-selectable $Z_{\delta c}$. The results of these evaluations did not noticeably differ from the earlier hover course results).

This first experiment led to the following conclusions:

1) The effect of Zw on helicopter handling qualities is less dramatic than suggested in the proposed revision to MIL-H-8501A (see Reference 4. The revision proposed a Level 1 limit of $-.25\ sec^{-1}$ and a Level 2 limit of $-.17\ sec^{-1}$ for all mission task elements other than dolphin and slalom tasks)

2) The change in steady state rate of climb per inch of collective input induced by variation of Zw is a strong effect when the task requires significant changes in rate of climb, such as the NOE task considered here. Tasks requiring more stabilization in the vertical axis with few large variations in steady-state climb rate are relatively insensitive to this same change.

Further examination of the results of this initial experiment raised the following questions:

- The evaluations for this experiment were flown with a relatively unrestricted T/W. Based on the outside air temperature and the aircraft weights encountered throughout the experiment the aircraft T/W was in the vicinity of 1.3. Are the results of this experiment valid at lower T/W values? What is the overall impact of T/W?

- Could the discrepancy between the results and the heave damping limits in the December 1985 proposed revision to MIL-H-8501A be due to the different stabilization levels in pitch and roll axes provided in this experiment compared to those provided in the heave damping experiments which formed the basis for the proposed revision. (The RCAH and ACAH control systems used in this experiment provided significantly increased aircraft pitch and roll stabilization which could allow more pilot capacity to be directed to other tasks such as vertical axis stabilization).

The goals of the second experiment were to resolve these two issues, to provide a better task scenario allowing more consistent NOE ratings and to investigate the impact of various dynamic response characteristics of the engines, governor and rotor system.

4.0 EXPERIMENT 2 - T/W, Zw AND ENGINE-ROTOR DYNAMICS

4.1 Design

The second experiment can be broken into two discrete parts. To evaluate the issues regarding heave damping and thrust to weight ratio, the first part of the experiment evaluated models in which the values of T/W and Zw were systematically varied. The values of these variables formed a matrix of three Zw levels (-0.65, -0.30 and -0.05 sec^{-1}) and three T/W levels (1.10, 1.05, 1.03). These first evaluations were all flown with a model approximately the basic Bell 205 engine-rotor system (model 0) which was regarded as possessing good dynamic characteristics.

The second part of the experiment was designed to address the issue of engine-rotor system dynamics and to this end four additional engine-rotor models were evaluated. To ensure that engine-rotor dynamics played the primary role in the evaluations, each of these models were flown with good T/W and Zw characteristics (1.10 and -0.65 sec^{-1} respectively).

4.1.1 Evaluation Course

To provide the best possible evaluation environment, the main task for this experiment differed from Experiment 1. Located in a marshy, uninhabited area, this nap of the earth course (Figure 10) incorporated all task elements of both courses used in the previous experiment except for the landing task. The course started from the hover. The evaluation pilot then accelerated the helicopter to 40 knots and, while maintaining airspeed to within 5 knots of this value, flew the aircraft over the three tree lines on the course in what is known as dolphin flight. A rapid deceleration to hover followed and, after a short hover period, the pilot executed a bob-up to acquire and sight on a target. The pilot was required to have the target stabilized in the aircraft sight for 2 seconds and to be in visual line-of-sight contact with the target for no more than 4 seconds. After the descent from the bob-up the evaluation pilot was required to perform a 180 degree pedal turn, rapidly accelerate to 40 knots and return to the start point by retracing the same dolphin course outbound. Due to unfavorable ground conditions over the NOE course, landings were evaluated separately at a different location. Each configuration was flown through the course a minimum of three times or was landed a minimum of five times before an evaluation form was filled out.

4.1.2 Vertical Axis Modelling

The maximum allowable thrust to weight value of any rotorcraft is usually dictated by limit values in either turbine inlet temperature or engine torque. In this experiment engine torque was selected as the limiting factor for T/W and a cockpit gauge was driven with the engine-rotor model torque signal, QE. The torque signal was scaled to place the torque gauge needle at the redline value whenever the configuration limit value of T/W was commanded. Along with the torque gauge, evaluation pilots were given an aural torque cue. This aural cue consisted of an 8 hz beeper which commenced 5% below redline and changed to a solid tone at and above redline. Configurations requiring torque at or above the redline (solid tone audio), either momentarily or continuously to complete any task, were considered to have handling qualities described by "adequate performance not attainable", a Level 3 Cooper Harper Rating, for that particular task.

Conventional rotorcraft exhibit a strong variation in power required, and thus a variation in available T/W, with forward speed. For hover and forward flight at low to moderate airspeeds, this variation is a reduction in power required with an increase in forward speed. For this section of the rotorcraft speed envelope the hover and hover manoeurving cases provide the most critical regime for T/W evaluations since a constant available power level provides the lowest vertical acceleration or climb capability in this range. The engine-rotor model used in this experiment did not try to model the rotorcraft power required variation with forward speed but instead held the available T/W capability of the modelled vehicle at a constant value. Analysis of the vertical axis model (Figure 4) shows that the maximum steady-state rate of climb of the model at any forward speed was given by:

$$R/C\ max = (T/W - 1)\ g/Zw$$

Further analysis of the model shows that the maximum vertical acceleration attainable by the vehicle, regardless of forward speed, and at any given vertical speed, w, was given by:

$$a_{Zmax} = (T/W - 1)\ g - Z_w \cdot W$$

While these relationships are also correct for true rotorcraft at the hover, their applicability at forward speeds can be debated. As the results will show, however, and as implied in an earlier portion of this section, it was the hover regime which provided the most critical requirements of helicopter T/W for this experiment.

The values of variables for the five engine-rotor system models used in the experiment are given in Table 5. As the collective step responses of these models show (Figures 11 - 15), the five models incorporated varying levels of torque overshoot, torque damping and rpm droop.

Bode plots of the collective to vertical velocity transfer function for the entire set of engine-rotor models used in the experiment are included as Figures 16 - 20. In each case, the frequency at -45° phase is consistent with the implemented Zw value of -0.65 sec^{-1} assuming a first order transfer function for $\frac{w(s)}{\delta c(s)}$. Similar statements can be made for the model 0 transfer functions with Zw = -0.30 and -0.05 sec^{-1} (Figures 22 and 23) if allowances are made for the poor low frequency resolution of the Fast Fourier Transform method used to create the Bode plots.

Bode plots displaying the transfer function of collective to torque for the five models are included as Figures 23 -27. In general, these two sets of Bode plots display small variations in vertical velocity response between models but show significant differences between the models in torque response to collective.

4.2 Results - T/W, Zw

The matrix of heave damping and thrust to weight ratio configuration matrix (incorporating engine-rotor model 0) was sampled by five evaluation pilots for a total of 44 discrete evaluation runs (excluding landing evaluations). For each configuration the Cooper Harper Handling Qualities Ratings were tabulated and are included as Figure 28. All configurations were not evaluated an equal number of times to allow a greater sampling emphasis on configurations which were judged to be key elements in the matrix. The mean Cooper-Harper ratings for each configuration and task are depicted in Figure 29. Examination of this data, along with evaluation pilot comments on each configuration, leads to a number of observations which will be discussed below.

For a Zw value of -0.65 sec^{-1}, the T/W value of 1.10 clearly results in a configuration with Level 1, that is "satisfactory", handling qualities. Reduction in the value of T/W to 1.03 degrades the aircraft handling qualities to Level 3 (adequate performance not attainable). Pilot comments about this series of models (Zw = -0.65 sec^{-1}, T/W = 1.10, 1.05, 1.03) indicate that perception of achievable aircraft performance was the primary cause of the handling qualities ratir trend. This 'performance' included both the abilities to achieve climb rates and to arrest sink rates. Specific pilot comments regarding these models included "marginal performance in the bob-up" for the 1.10 T/W case and "insufficient performance in the bob-up" for the 1.03 T/W case. Figure 30 graphically displays this performance degradation by representing typical altitude time histories for the bob-up manoeuvre.

In one example, the evaluation pilot, when confronted with the poor bob-up performance of the Zw = -0.65 sec^{-1}, T/W = 1.03 case, tried to enhance the aircraft climb performance by 'off-loading' the tail rotor. This technique, commonly used for low T/W helicopter operations at the hover, allows the normal tail rotor torque to be applied to the main rotor while the aircraft is allowed to change heading in response to the main rotor applied torque. While the use of this technique did not, in fact, provide increased performance of the aircraft due to the model implementation used here, the incident did demonstrate the severity of the performance problem at the T/W value of 1.03. For this specific example the aircraft model received a Cooper Harper rating of 8 for the bob-up task.

The effect of T/W value (for a fixed Zw of $-0.65\ sec^{-1}$) can also be seen in the pilot comments and flight path time histories of the dolphin manoeuvre. For the lower T/W values, pilot comments consistently described the requirement for increased collective control anticipation, or lead, especially during descending phases of flight. This required lead resulted in dolphin flight paths which were smoother and more gentle than those considered desirable and achievable with the 1.10 T/W configuration. Example dolphin manoeuvre flight paths for models incorporating the two extreme T/W values are shown as Figure 31.

Based on pilot rating data, pilot comments and achieved task performance, all for models with a constant heave damping level of Zw = $-0.65\ sec^{-1}$, the Level 1 and 2 handling qualities boundaries for T/W can be placed at 1.08 and 1.04 respectively.

The effect of a reduction in heave damping in the presence of constant T/W also involves changes in handling qualities ratings, but in a different manner. As Figure 28 shows, for a constant T/W value of 1.10 a change in Zw from -0.65 to $-0.30\ sec^{-1}$ causes a slight improvement in handling qualities. Further change in Zw to $-0.05\ sec^{-1}$ causes a degradation towards Level 2 handling qualities. This behaviour is attributed to the trade-off between vertical axis stability and performance. For the first heave damping reduction, it is suspected that the pilots perceive the increase in climb performance due to reduced heave damping and are able to tolerate the stability reduction. The second decrease, however, causes the vertical axis stabilization workload to surpass the satisfactory level, resulting in Level 2 ratings for some manoeuvres, despite the even larger performance increase.

Based on the results and the ratings of experiment 1 a Level 1 limit of Zw is placed at -0.20 sec^{-1}. The data collected in the two experiments does not support the placement of a Level 2 limit for Zw.

Figure 32 depicts the handling qualities level boundaries for T/W and Zw proposed by three different sources, those generated by this series of experiments (designated by NRC), those generated by experiments performed on the NASA-Ames VMS (Reference 12) and those proposed by STI for the revision of MIL-H-8501A (Reference 5). Bob-up task ratings from NASA and NRC experiments are also shown on this figure. The data demonstrate a reasonable agreement between the NRC boundaries and those proposed for the MIL-H-8501A revision although the NRC boundaries are more lenient. The NASA boundaries, however, do not depict the same trends as the other two sources. Comparison of bob-up task ratings between NRC and NASA experiments shows general agreement in most areas but a marked disagreement for T/W = 1.10 and lower heave damping values. The two NASA ratings in this area (6.0 and 6.2 as shown in Figure 32) represent the primary cause of disagreement between handling qualities level boundaries. In this area of the T/W, Zw matrix, NRC data has shown that the pilots accept a reduction in vertical stability and therefore an increase in vertical stabilization workload in return for an increase in vertical axis performance and, in general, rate the Zw = -0.30 sec^{-1} model as having slightly better handling qualities than the Zw = -0.65 sec^{-1} model. In the NASA experiment, however, the fidelity of visual and motion cues inherent in the simulator may cause this same vertical stability decrement to result in unacceptable levels of pilot stabilization workload. A stronger insistence on height stability for the NASA bob-up task may have aggravated this situation.

More recent NASA experiments on this subject, results of which have not yet been published (Reference 13), tend to support the NRC generated handling qualities level boundaries for Zw and T/W.

An additional result of the T/W, Zw investigation relates to the implementation of the torque audio cue. While pilots did appreciate the torque cues provided by the 5% warning beeper, pilot comments suggested that a better audio signal could provide the cues necessary for more complete torque utilization. In particular, the torque beeper did not give the pilot precise information on how close he was to torque redline or on the rate of approach to torque redline. An audio beeper with frequency scaled to the proximity of the engine torque to torque redline would provide these additional cues and would be a significant improvement on the torque audio cue system used in this experiment.

4.3 Results - Engine-Rotor Dynamics

Analysis of the engine-rotor models was based upon 16 evaluations performed by 4 pilots. Each of four engine-rotor models (1, 2, 4 and 6)* was evaluated with a 1.10 T/W value and a -0.65 sec^{-1} Zw value (values previously determined as Level 1). Model 0, the baseline model, was evaluated 9 times by 5 pilots during the previous T/W, Zw phase of the experiment at these same T/W and Zw values.

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* Models 3 and 5 were development models which were not evaluated.

Cooper Harper Handling Qualities Ratings for each of the engine-rotor models and tasks are included as Figure 33. These ratings clearly show that the configurations with engine-rotor models 0 and 6 had Level 1 handling qualities for all tasks in the nap of the earth course. Evaluations of these two models have the best inter-pilot agreement and pilot comments also reflect the Level 1 assignment. Ratings for engine-rotor models 1, 2 and 4 are significantly different in nature. The rating data for these models has considerably more scatter, a general trait of systems with poor handling qualities. While an average of the ratings for each model might in some cases provide a bare Level 1 rating (3.5), the range of ratings for each model suggests that each is the cause of at least Level 2 if not Level 3 handling qualities.

The December 1985 proposed revision to MIL-H-8501A suggests that the vertical velocity response to a step collective input must conform to a suitable shape to provide satisfactory handling qualities. This suitable shape is analytically described by an envelope of tr_{25} and vertical velocity shaping parameter, $(tr_{50} - tr_{25})/(tr_{75} - tr_{50})$, where tr_n is the rise time of vertical velocity from the onset of a step input in collective to the time when the vertical velocity reaches n percent of the steady-state value. This envelope, derived from handling qualities data of Corliss (1983) and Hindson (1986) is depicted in Figure 34. Plotting the handling qualities ratings of configurations incorporating the five engine-rotor models evaluated in this experiment on Figure 34 reveals that the velocity shape criterion predicts models 0 and 6 to be Level 2 in handling qualities and model 4 to have borderline Level 1 characteristics. Since these assignments are contrary to the subjective handling qualities rating data gathered on the models, further investigation is required.

The foundation data for the velocity shape criterion were ratings of configurations in which torque and rpm were not variables of concern. That is, the values of torque and rpm displayed to the pilot were constant, ideal indications. In the experiment described here, however, the torque and rpm indications were varied in coordination with the engine-rotor model being simulated. In all evaluations of these models pilot comments reflected 'torque dynamics' as the primary cause of lower handling qualities ratings. It is plausible to assume that the predicted borderline Level 1 handling qualities of the configuration with the model 4 engine-rotor system were degraded to the almost Level 3 rating achieved in this experiment due to the impact of the torque monitoring task. It is less likely, however, that the handling qualities of the configuration with the model 0 engine-rotor system were enhanced by the torque monitoring task. Since the velocity shaping parameter criterion fails to consider the torque monitoring workload associated with configurations having low T/W values its prediction of handling qualities level must be regarded with caution.

While the shape of the velocity response to a step collective input does not appear to be a significant factor, this experiment does demonstrate the overriding importance of torque and rpm control. Analysis of the rating data with emphasis on torque characteristics provides insight into the observed rating trends. Evaluation of models 1, 2 and 4 provided rating data with a large range of value. Pilot comments on these models stated, as discussed earlier, that the monitoring and control of engine torque accounted for a major source of pilot workload. Pilots also noted that the torque characteristics created the need to alter pilot control strategy to add more lead; that is to anticipate required collective inputs, and to 'ramp' large inputs in collective. In all cases pilots reduced collective sensitivity by 50 to 75% for models 1, 2 and 4.

It is postulated that the success that each pilot had (and thus the handling qualities rating assigned) with models 1, 2 and 4 was directly related to the frequency content of the pilot in the critical .6 to 2.5 rad/sec range since this band of frequencies would excite the resonance of the model torque response. The altered strategy discussed by each pilot was an attempt to minimize this critical frequency content. The power spectral densities (PSD) of each pilot's collective activity for a portion of the dolphin task segment, Figures 35 - 39, support this hypothesis. While all 4 evaluation pilots displayed reduced collective input power levels above approximately 0.6 rad/sec for models 1, 2 and 4, pilots D and E typically had the highest power levels in this area. These two pilots also rated the handling qualities of models 1 and 2 significantly poorer than pilots B and C. Model 4 handling qualities ratings do not seem as sensitive to this power reduction characteristic. Collective input power spectral densities for models 0 to 6 were roughly similar for all evaluation pilots.

The evaluations of 'torque dynamics' demonstrated by these 5 engine-rotor models suggest that the occurance of a resonant peak in the collective to torque transfer function is the major source of lower handling qualities ratings. Based on the transfer functions of configurations evaluated, it appears that a 3 db resonant peak, measured from either the low frequency asymptote or possibly the 0.2 rad/sec amplitude ratio value is a Level 1 handling qualities limit for satisfactory torque response to collective. This 3db value is the peak height measured for model 6. The rating differences between model 4 and models 1 and 2 also suggest a benefit of having any resonant peak at as high a frequency as possible. This suggestion clearly relates to moving the torque 'resonance sensitive frequency' as far away as possible from the pilot's frequency content. Pilot behaviour, when confronted with these resonance-prone models, also suggests this benefit since pilot frequency content is reduced through collective lead, ramping of inputs and a decrease in collective sensitivity. As mentioned earlier, the pilot's success in accomplishing this frequency content reduction in piloting technique was a major factor in model evaluation.

5.0 CONCLUSIONS

The results of the investigations presented here lead to the following conclusions:

- Level 1 and Level 2 handling qualities minimums of thrust to weight ratio should be 1.08 and 1.04 respectively. These values are in close agreement but slightly more lenient than the limits suggested in the December 1985 proposed revision to MIL-H-8501A (Reference 5).

- The minimum heave damping for Level 1 handling qualities corresponds to $Zw = -0.20\ sec^{-1}$. No Level 2 limit is supported by the data collected during this research.

- The handling qualities rating trends for configurations with T/W = 1.10 suggests that the provision of heave damping at the expense climb performance is not desirable in all cases.

- A possible benefit in handling qualities is suggested by the shifting of collective to torque resonant peaks to the highest possible frequency.

- In cases where T/W is a dominant factor, and thus an emphasis is placed on torque control, the vertical velocity shaping parameter appears to have little signficance in determining Level 1 handling qualities.

6.0 ACKNOWLEDGEMENTS

The authors gratefully acknowledge the following evaluator pilots for their assistance and expertise:

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	Experiment 1	Experiment 2
Pitch		
stick force gradient	.5 lb $inch^{-1}$	.6 lb $inch^{-1}$
breakout	.5 lb	.9 lb
Roll		
stick force gradient	.5 lb $inch^{-1}$	.6 lb $inch^{-1}$
breakout	.5 lb	.5 lb
Yaw		
stick force gradient	6.5 lb $inch^{-1}$	6.5 lb $inch^{-1}$
breakout	1 lb	1 lb

TABLE 1: STICK CHARACTERISTICS

Pilot	A	B	C	D	E
Total Flying Hours	2400	8600	7500	3800	1350
Rotary Wing	150	1220	1500	2200	560
VTOL (not incl. rotary wing)	1000	—	—	—	—
Fixed Wing (incl. VTOL)	2250	7380	6000	1600	790
Test Pilot School	✓	✓	✓	✓	—

Table 2: EVALUATION PILOT RELEVANT EXPERIENCE

	Bandwidth Pitch	Bandwidth Roll	Overall Hover Course Handling Qualities Rating
ACAH	2.74 rs^{-1}	3.10 rs^{-1}	2-2 1/2
RCAH	2.00 rs^{-1}	2.80 rs^{-1}	3
RD	1.80 rs^{-1}	3.50 rs^{-1}	2

TABLE 3: CONTROL SYSTEMS BANDWIDTH

Model Number	Zw effective values (sec^{-1}) Hover	40 knots	80 knots
1	-0.05	-0.50	-0.60
2	-0.65	-0.80	-0.10
3	-1.25	-1.10	-1.50

TABLE 4: Zw EFF VALUES (sec^{-1}) IMPLEMENTED IN EXPERIMENT 1.

Model No.	ξ	α	G2	I_r (slug - ft^2)
0	.7	2	10	1500.
1	.7	.5	10	200.
2	.7	.5	40	200.
4	.7	.5	40	1500.
6	1.0	.25	5	200.

G1 = 20

K1 = .170

K2 = .0893

TABLE 5: ENGINE - ROTOR MODELS

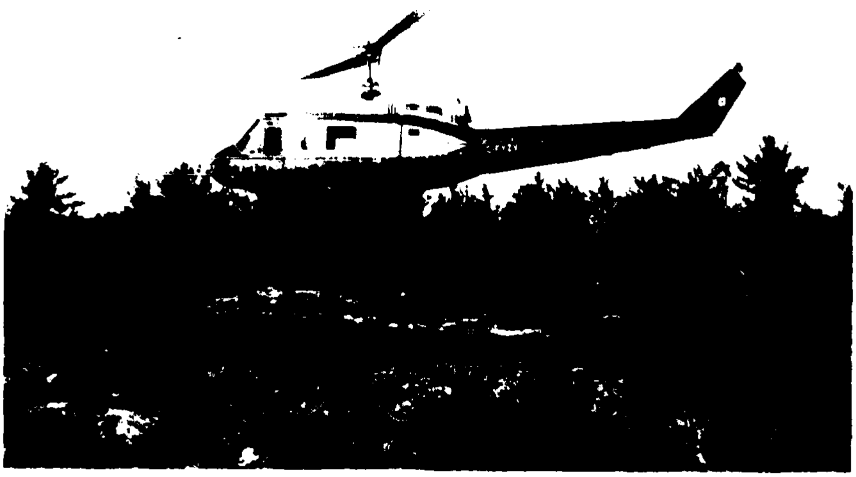
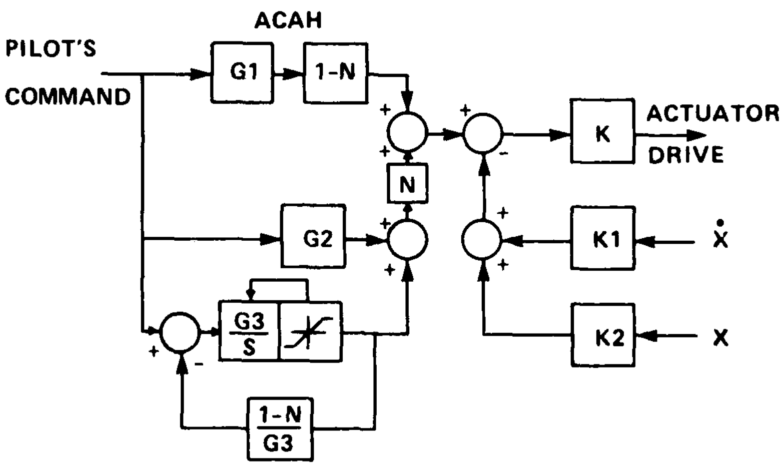


FIG. 1: THE NAE BELL 205 AIRBORNE SIMULATOR



FOR ATTITUDE COMMAND/ATTITUDE HOLD – N = 0, K1 = 0
RATE COMMAND/ATTITUDE HOLD – N = 1, K2 = 0
RATE DAMPED – N = 0, K2 = 0

G1, G2, G3 – CONTROL SYSTEM GAINS
K1, K2 – FEEDBACK GAINS
K – ACTUATOR GAIN

FIG. 2: PITCH AND ROLL CONTROL SYSTEMS

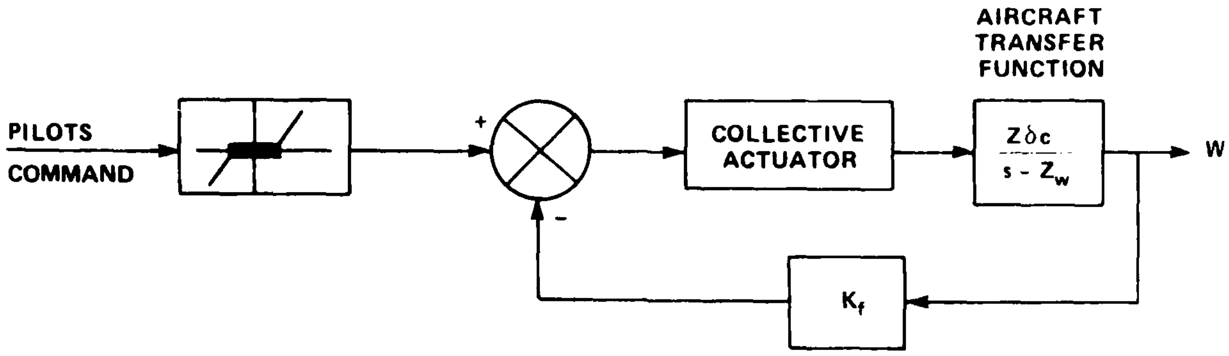


FIG. 3: HEAVE DAMPING AUGMENTATION SYSTEM – EXPERIMENT 1

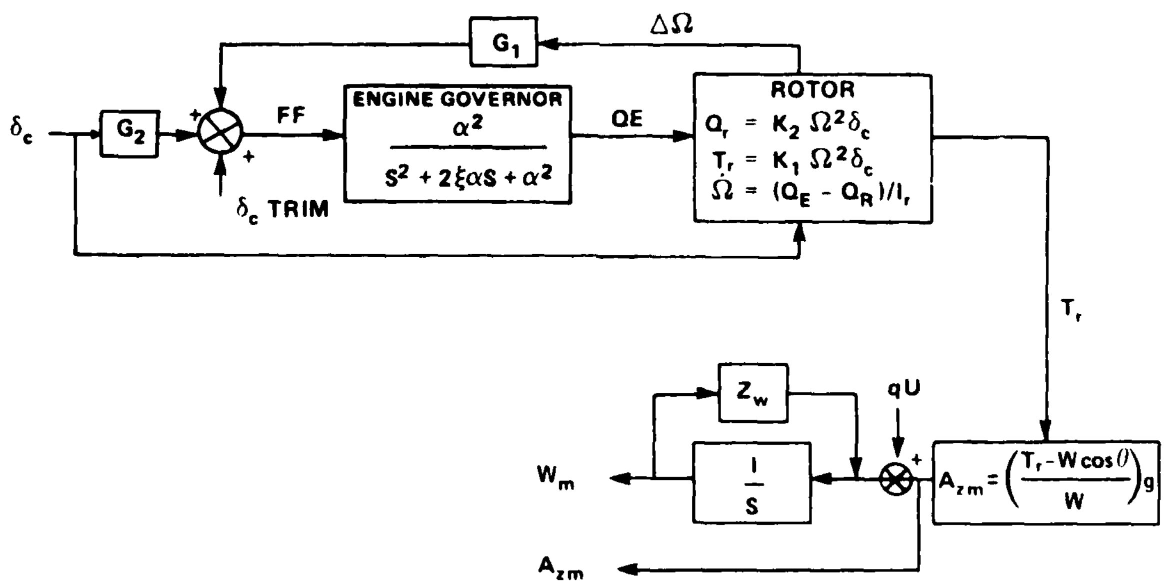


FIG. 4: VERTICAL CHANNEL MODEL-FOLLOWING SYSTEM – EXPERIMENT 2

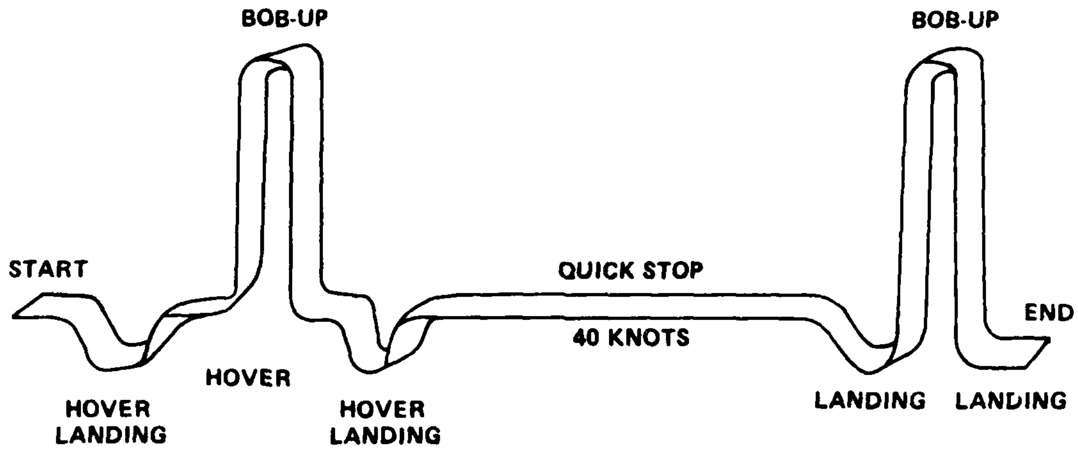


FIG. 5: HOVER COURSE – EXPERIMENT 1

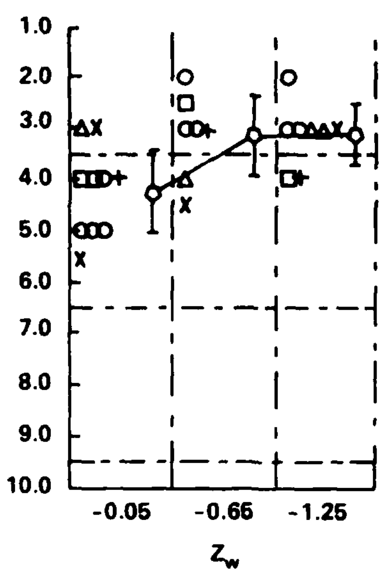


FIG. 6: OVERALL COOPER-HARPER RATINGS – HOVER COURSE, RCAH

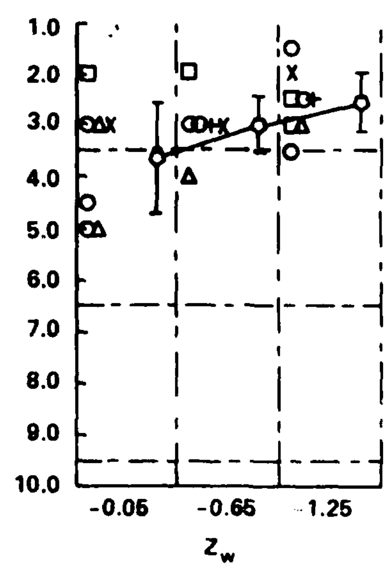


FIG. 7: OVERALL COOPER-HARPER RATINGS – HOVER COURSE, ACAH

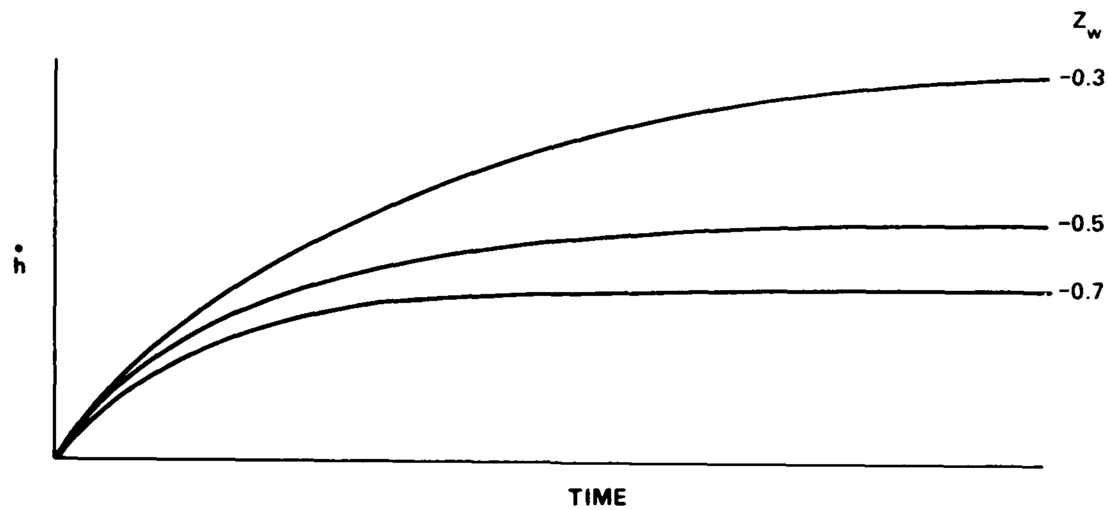


FIG. 8: STEP RESPONSE, Z_{δ_c} FIXED

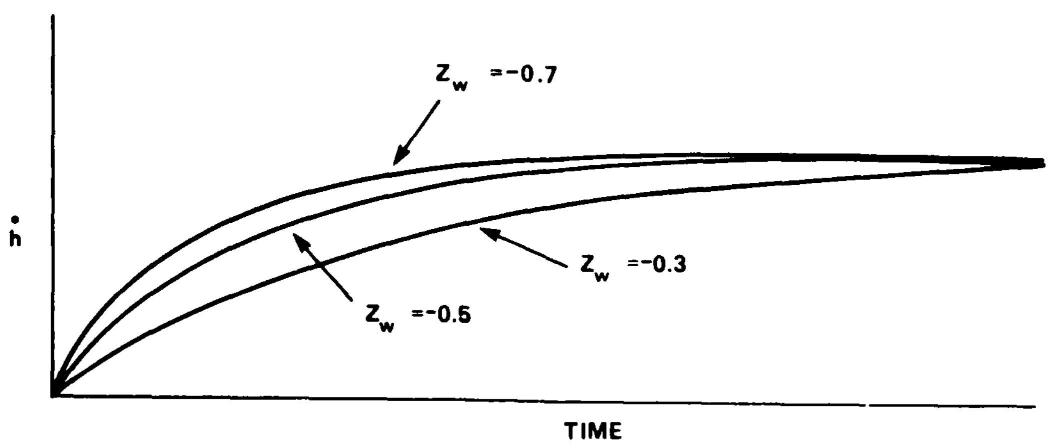


FIG. 9: STEP RESPONSE, Z_w/Z_{δ_c} FIXED

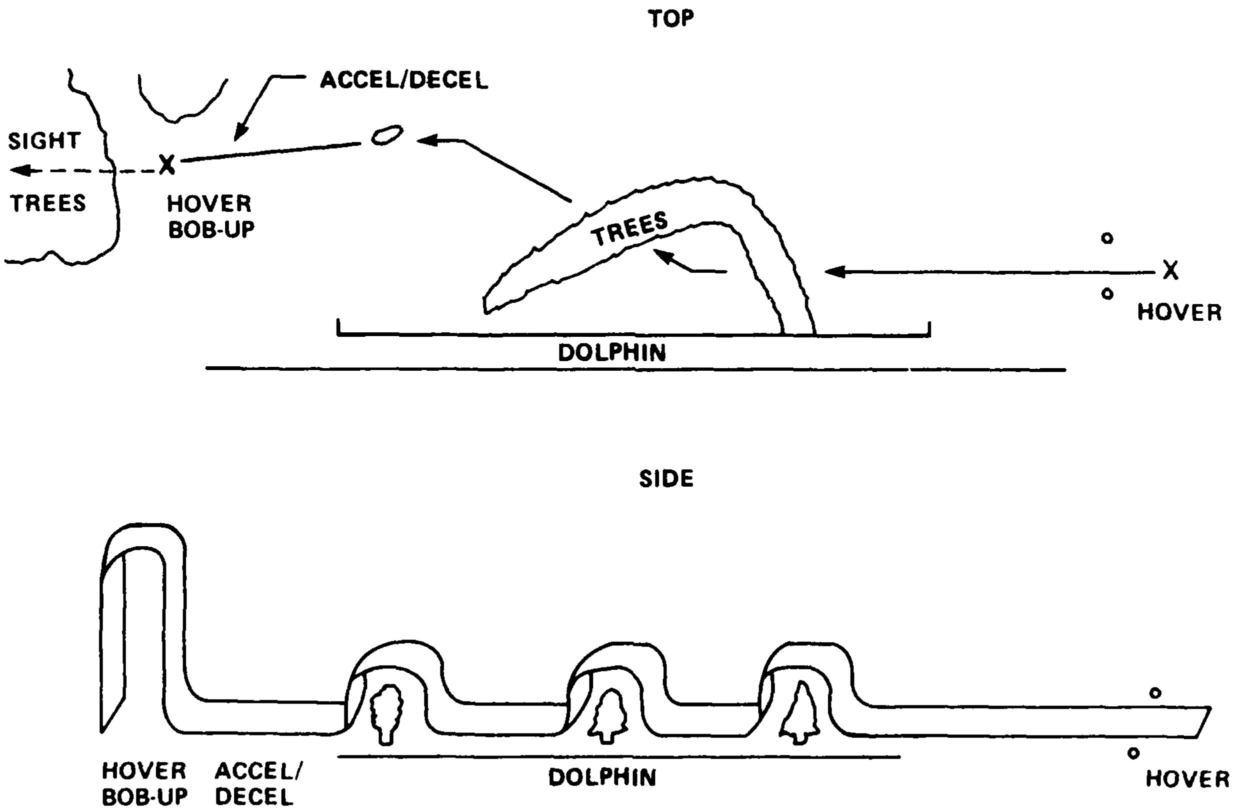


FIG. 10: NOE COURSE – EXPERIMENT 2

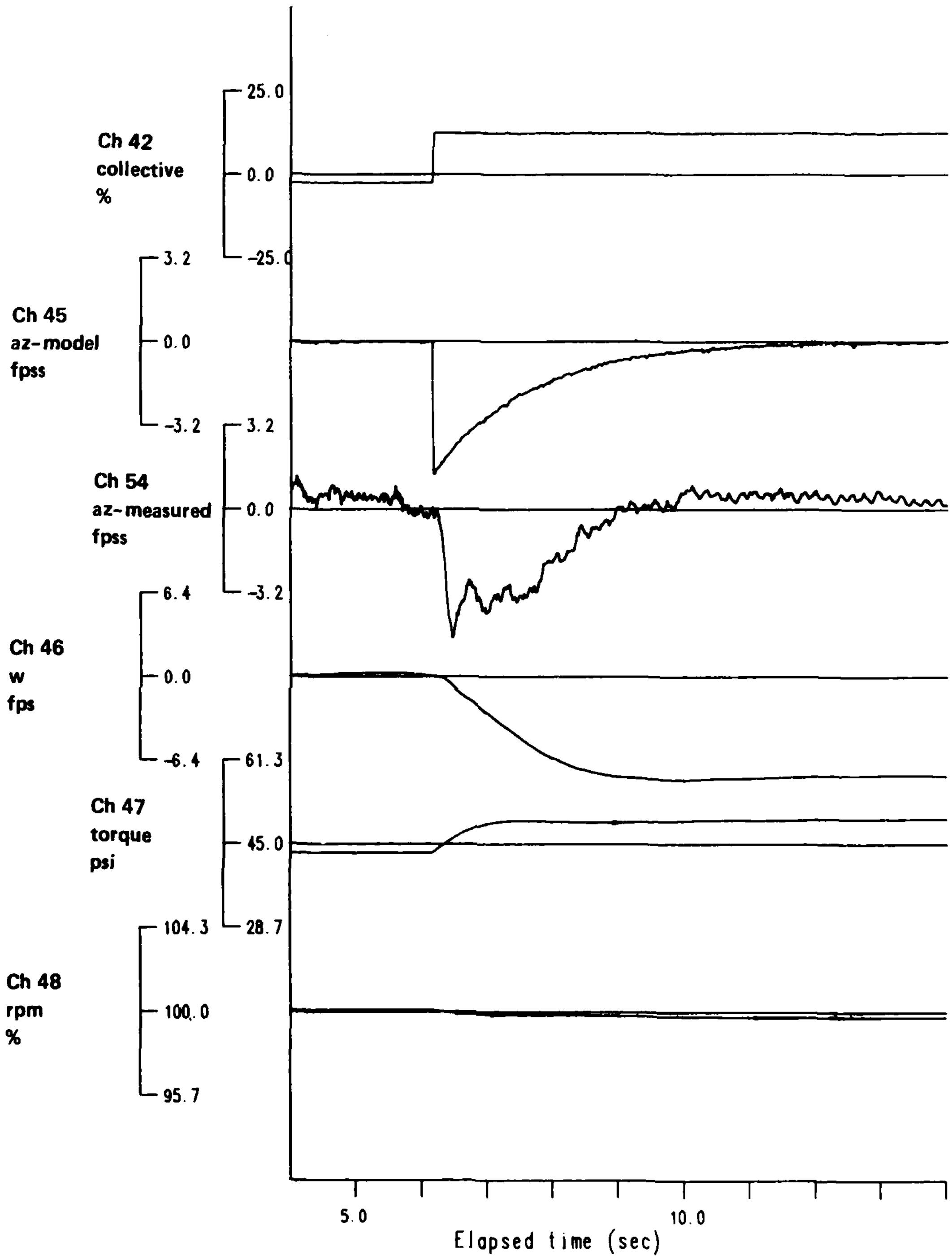


FIG. 11: COLLECTIVE STEP RESPONSE, ENGINE-ROTOR MODEL 0

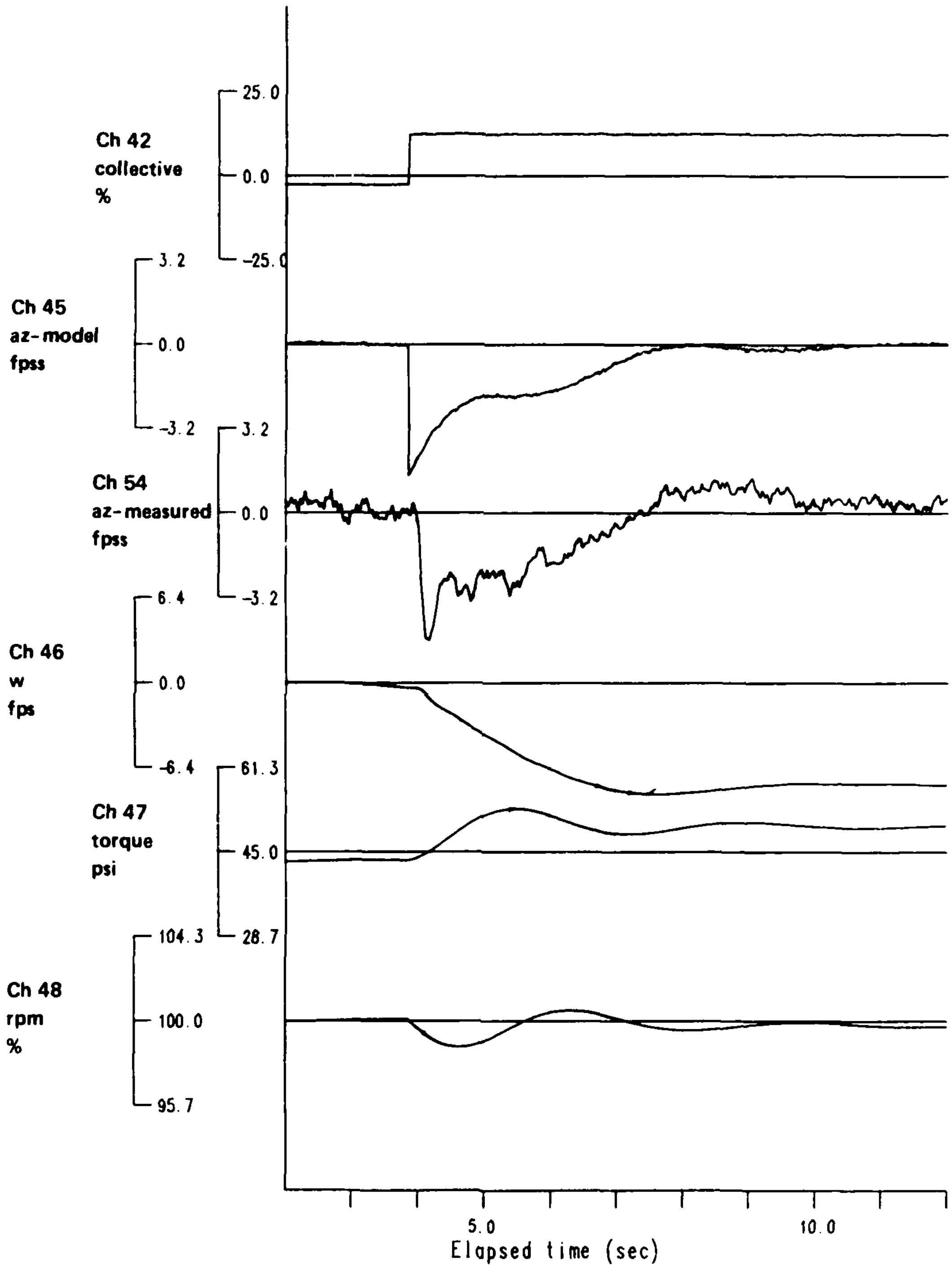


FIG. 12: COLLECTIVE STEP RESPONSE, ENGINE-ROTOR MODEL 1

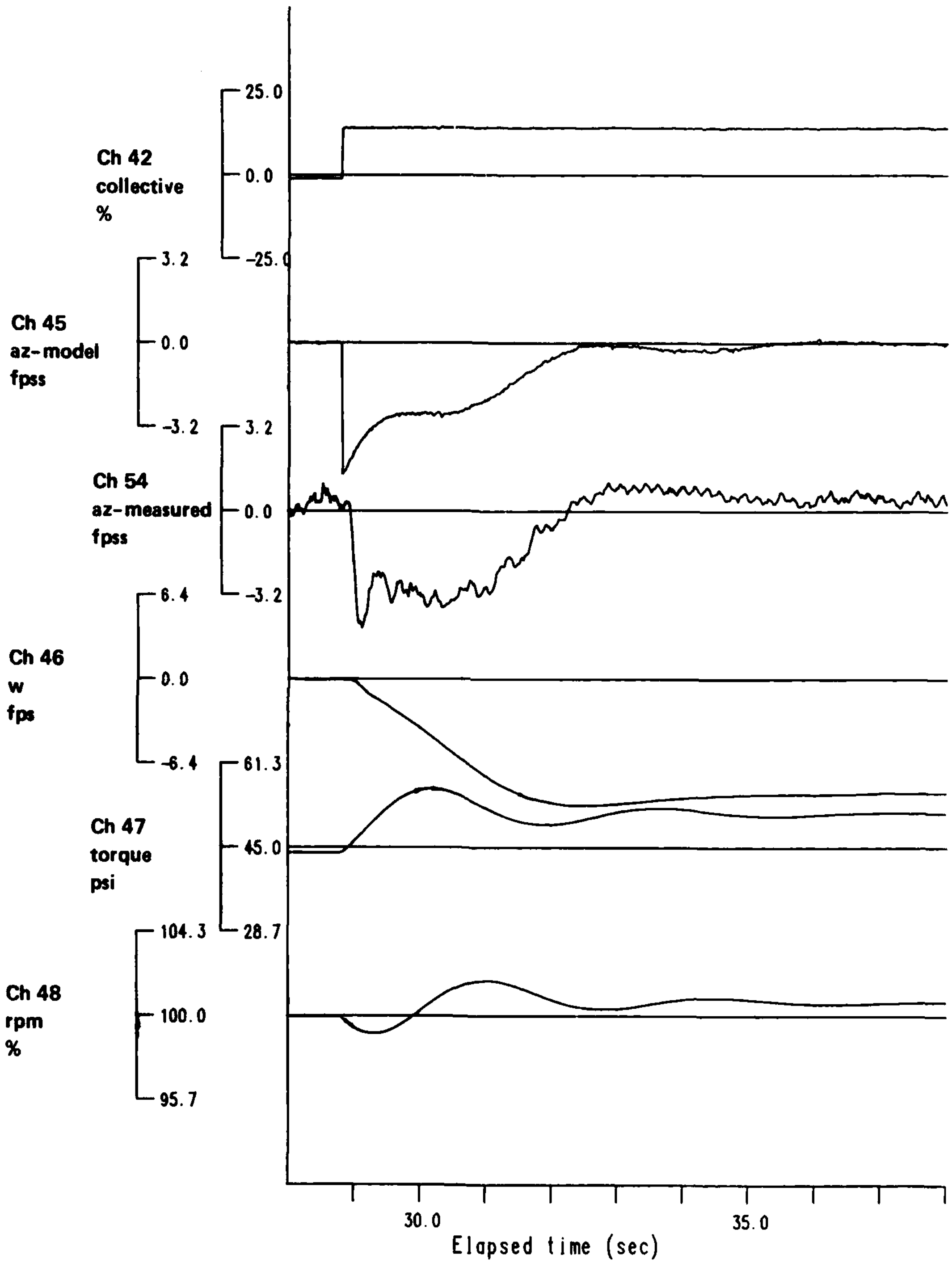


FIG. 13: COLLECTIVE STEP RESPONSE, ENGINE-ROTOR MODEL 2

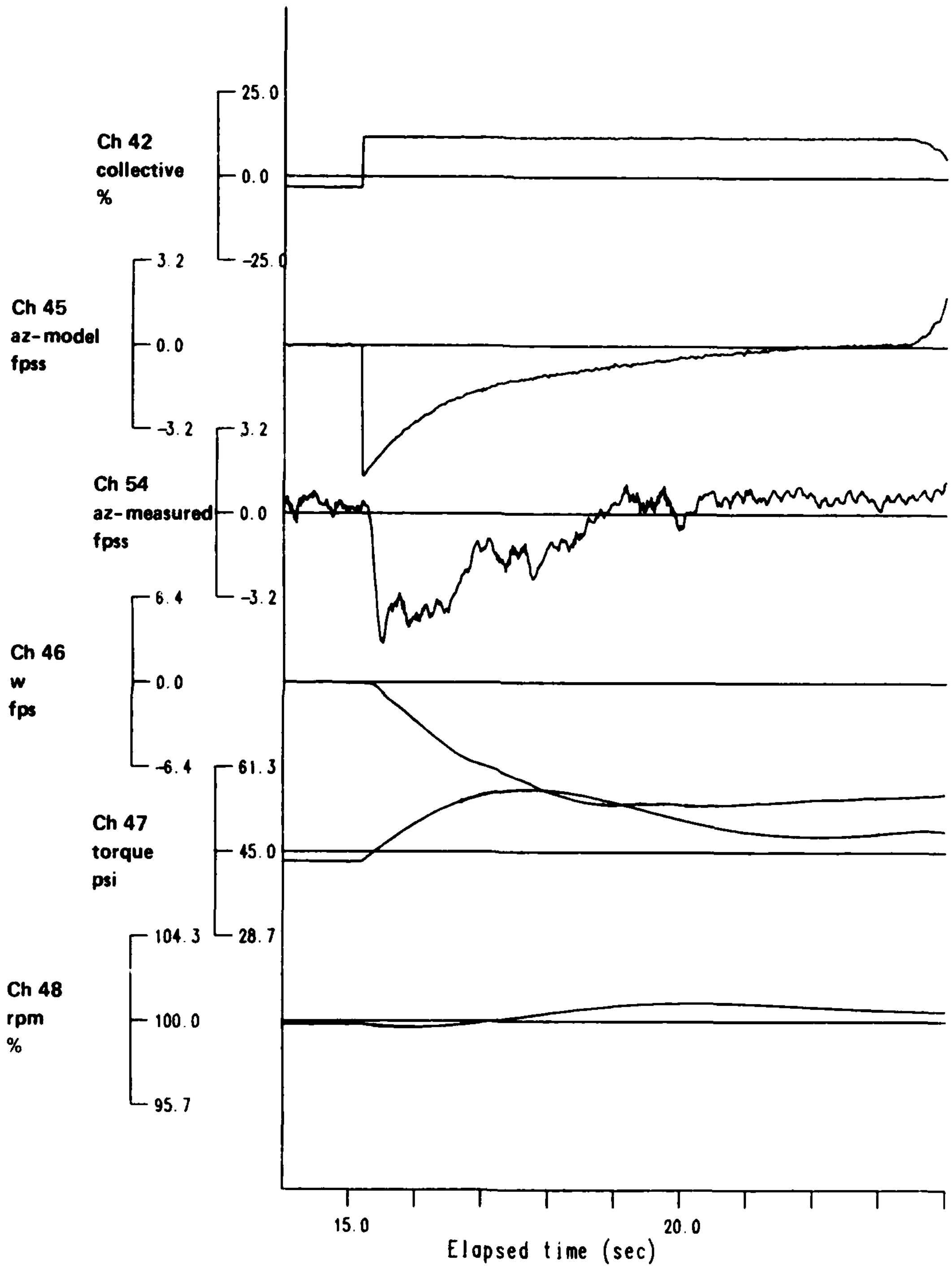


FIG. 14: COLLECTIVE STEP RESPONSE, ENGINE-ROTOR MODEL 4

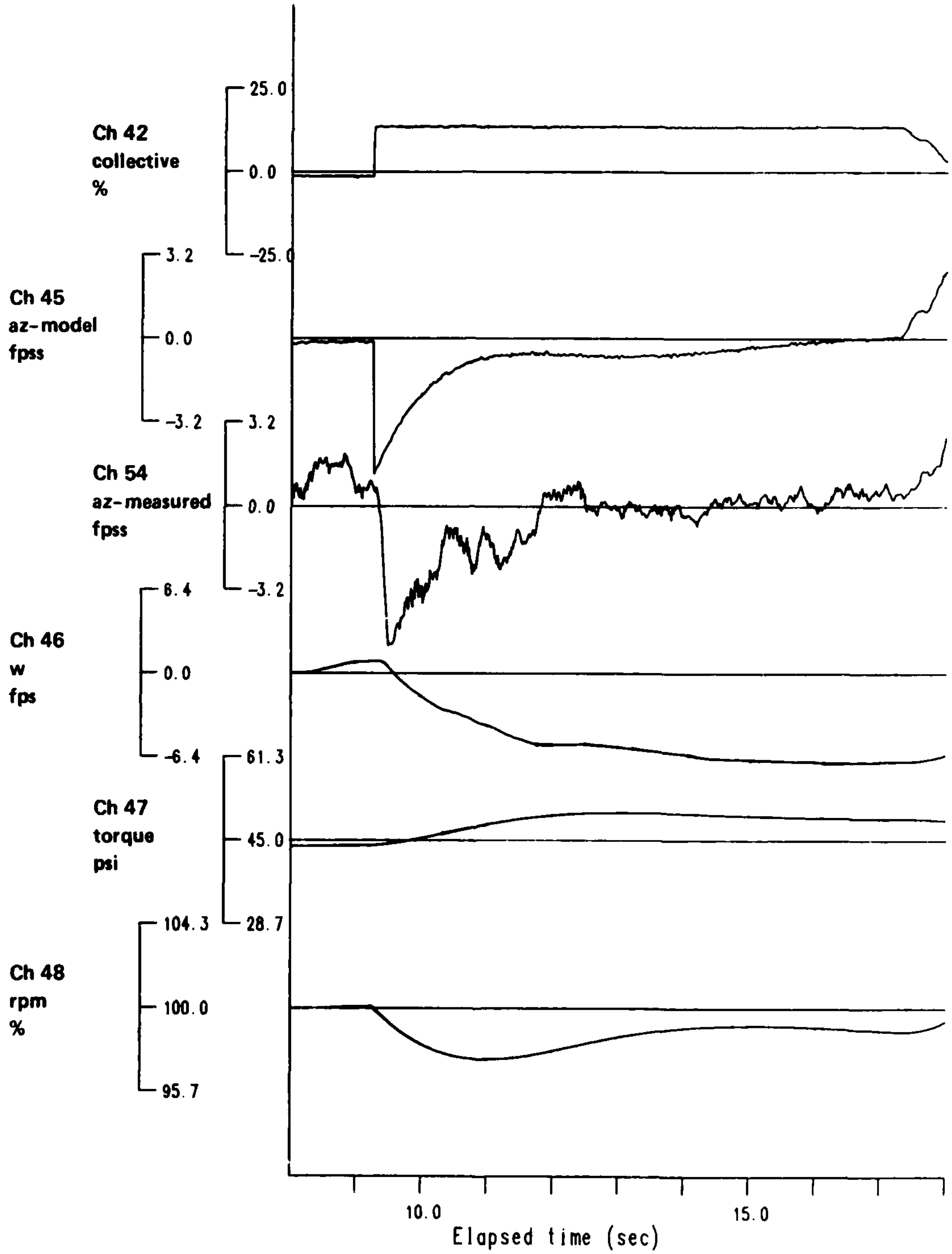


FIG. 15: COLLECTIVE STEP RESPONSE, ENGINE-ROTOR MODEL 6

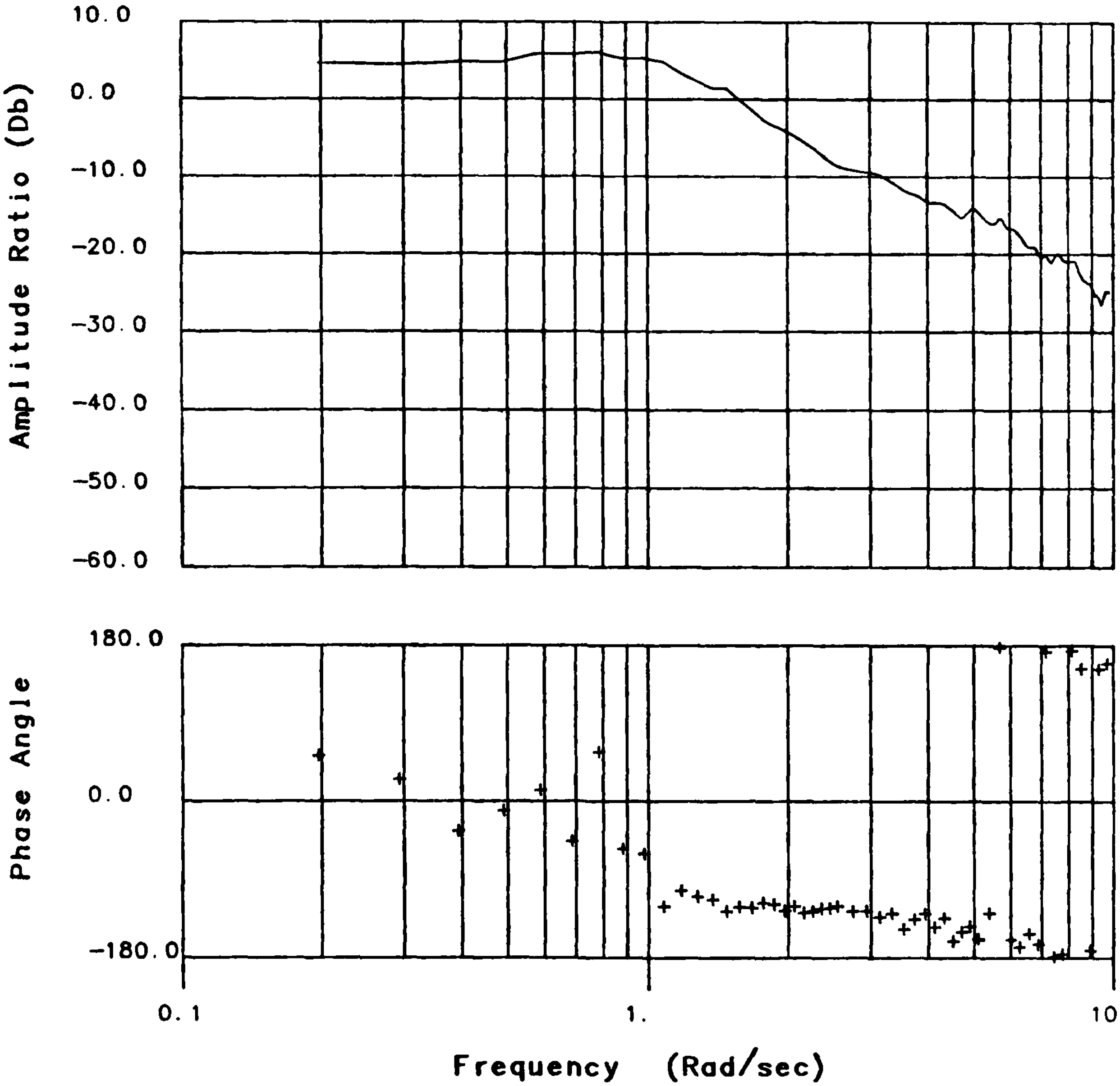


FIG. 16: BODE PLOT, VERTICAL VELOCITY/COLLECTIVE,MODEL 0

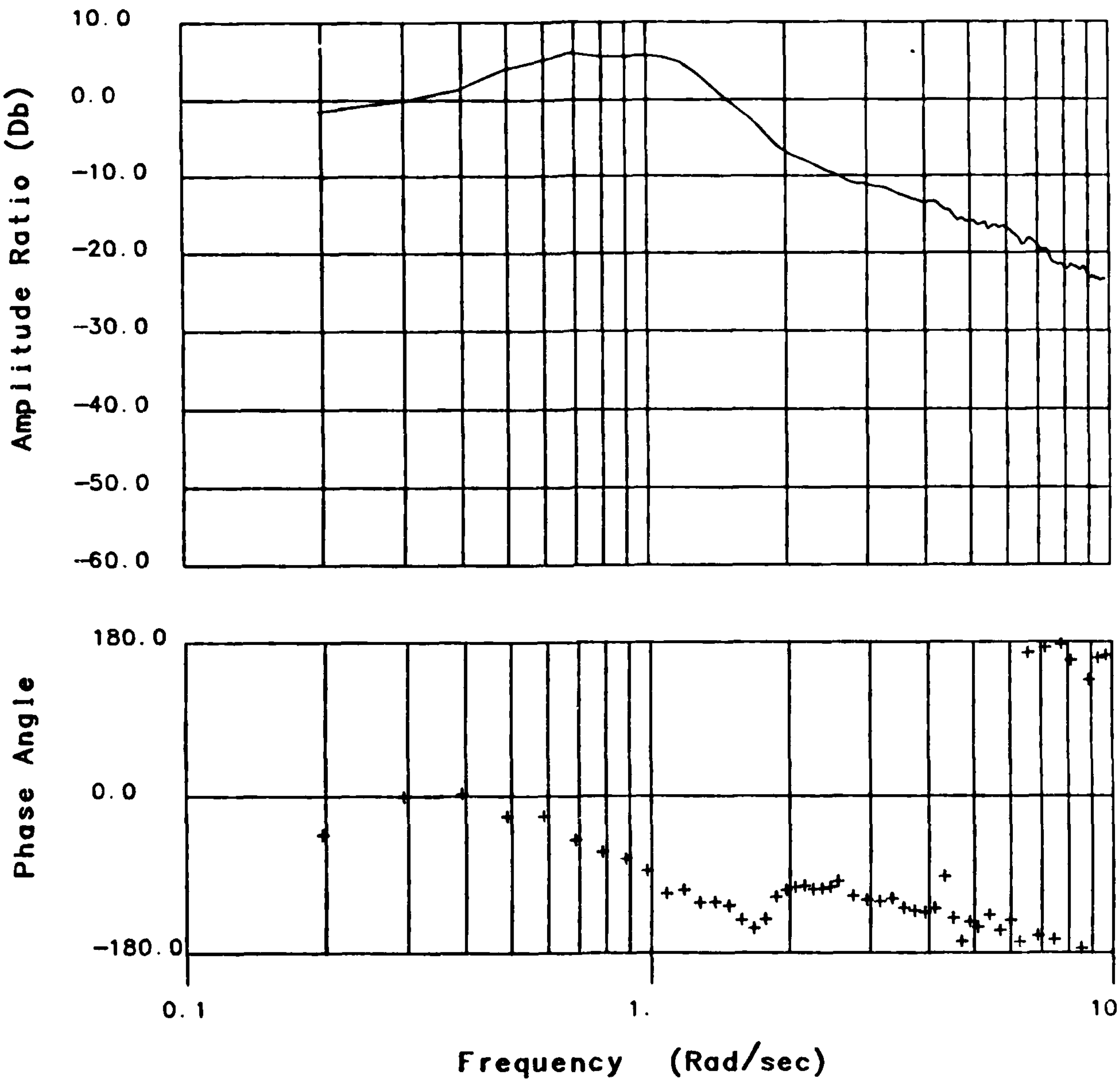


FIG. 17: BODE PLOT, VERTICAL VELOCITY/COLLECTIVE, MODEL 1

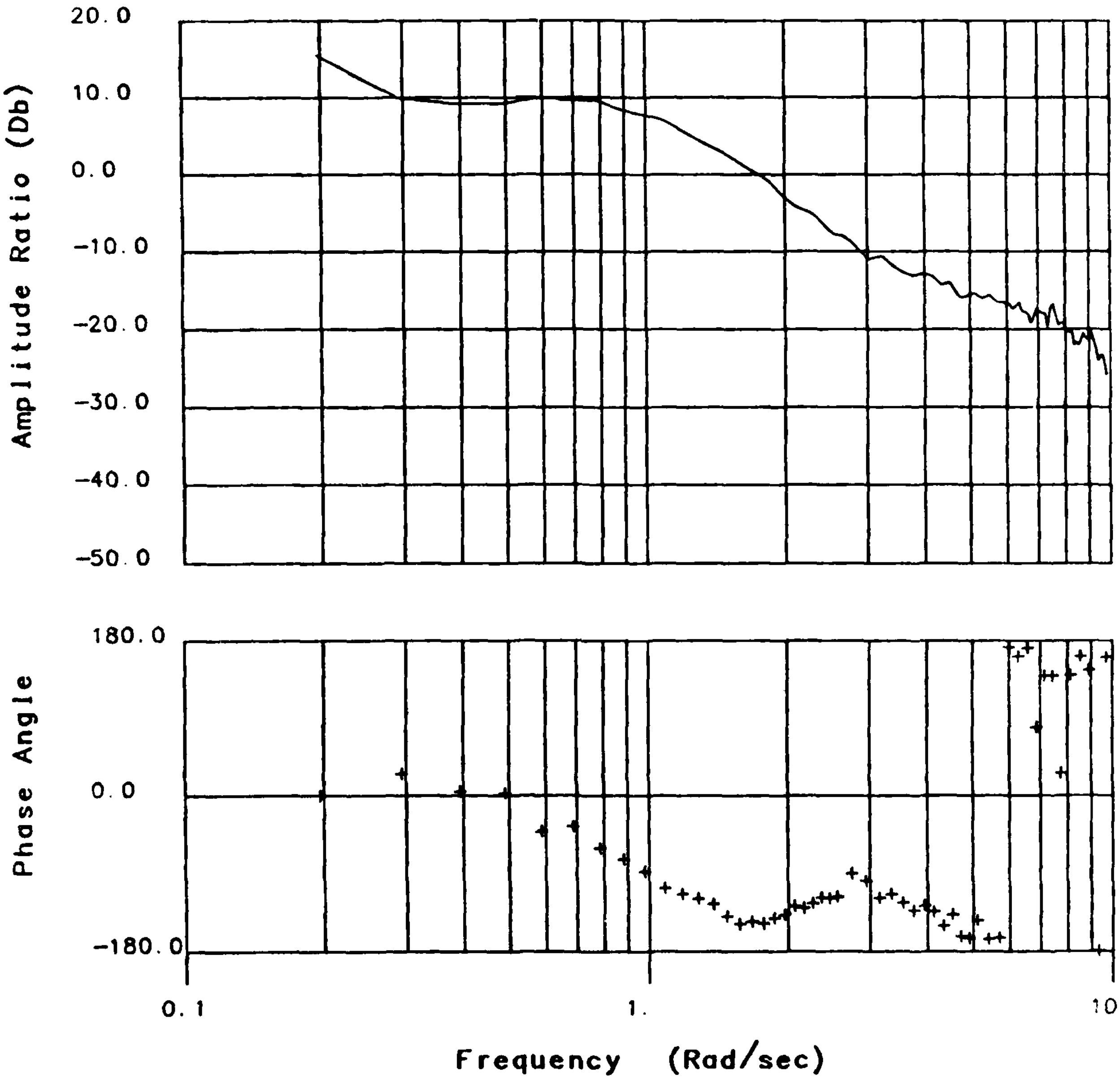


FIG. 18: BODE PLOT, VERTICAL VELOCITY/COLLECTIVE,MODEL 2

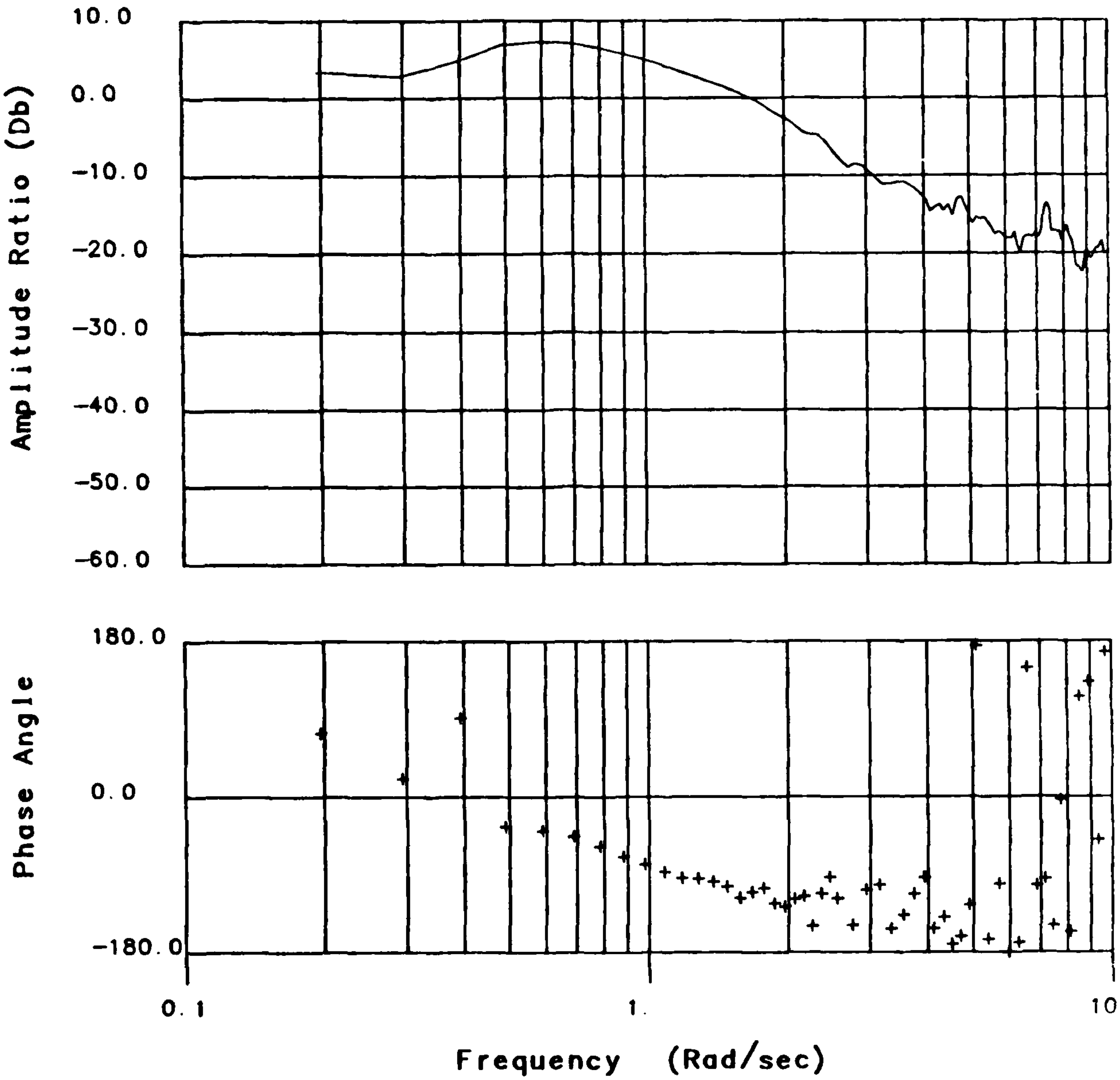


FIG. 19: BODE PLOT, VERTICAL VELOCITY/COLLECTIVE, MODEL 4

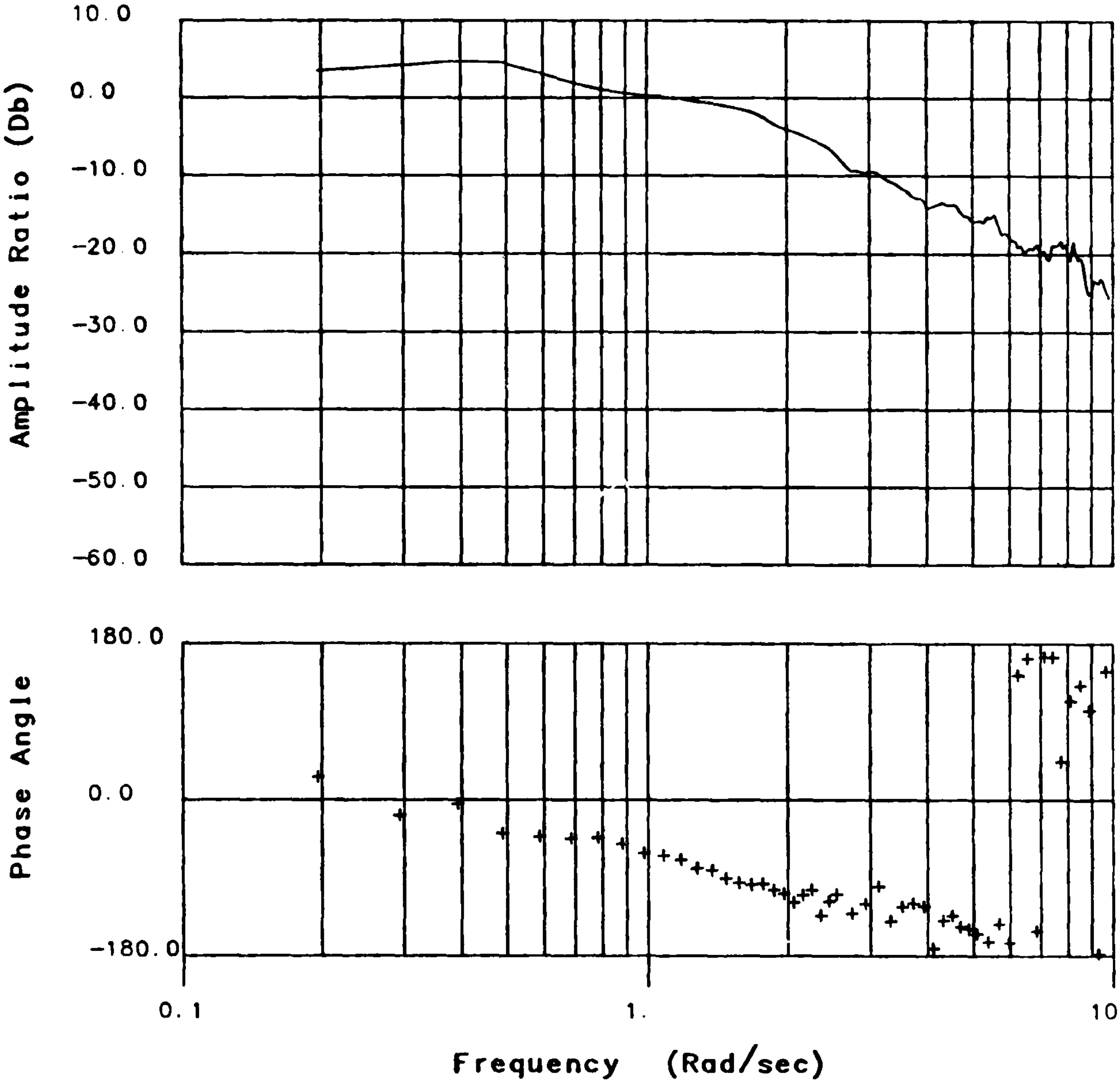


FIG. 20: BODE PLOT, VERTICAL VELOCITY/COLLECTIVE, MODEL 6

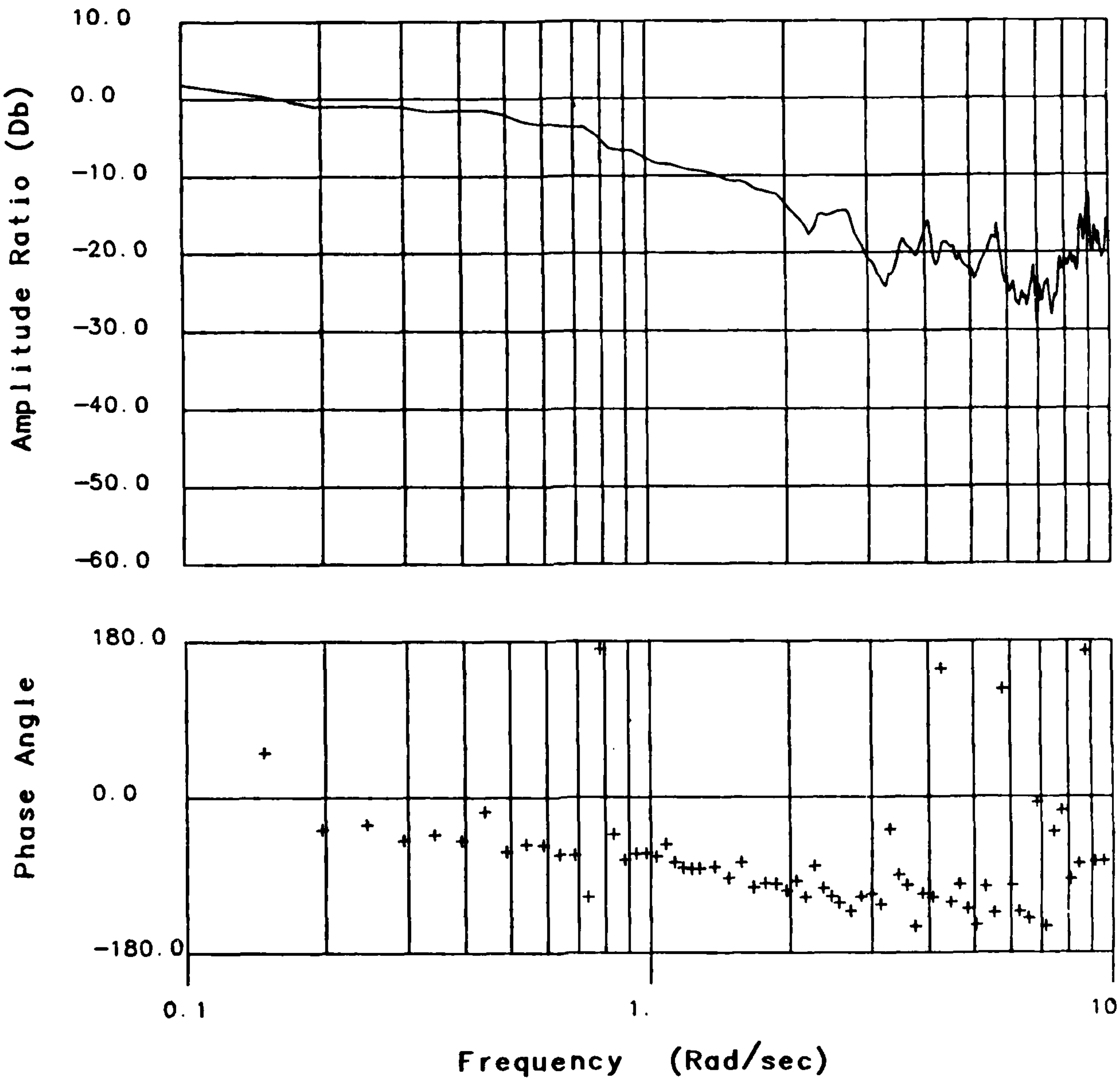


FIG. 21: BODE PLOT, VERTICAL VELOCITY/COLLECTIVE, MODEL 0
WITH Z_w = $-0.30\ sec^{-1}$

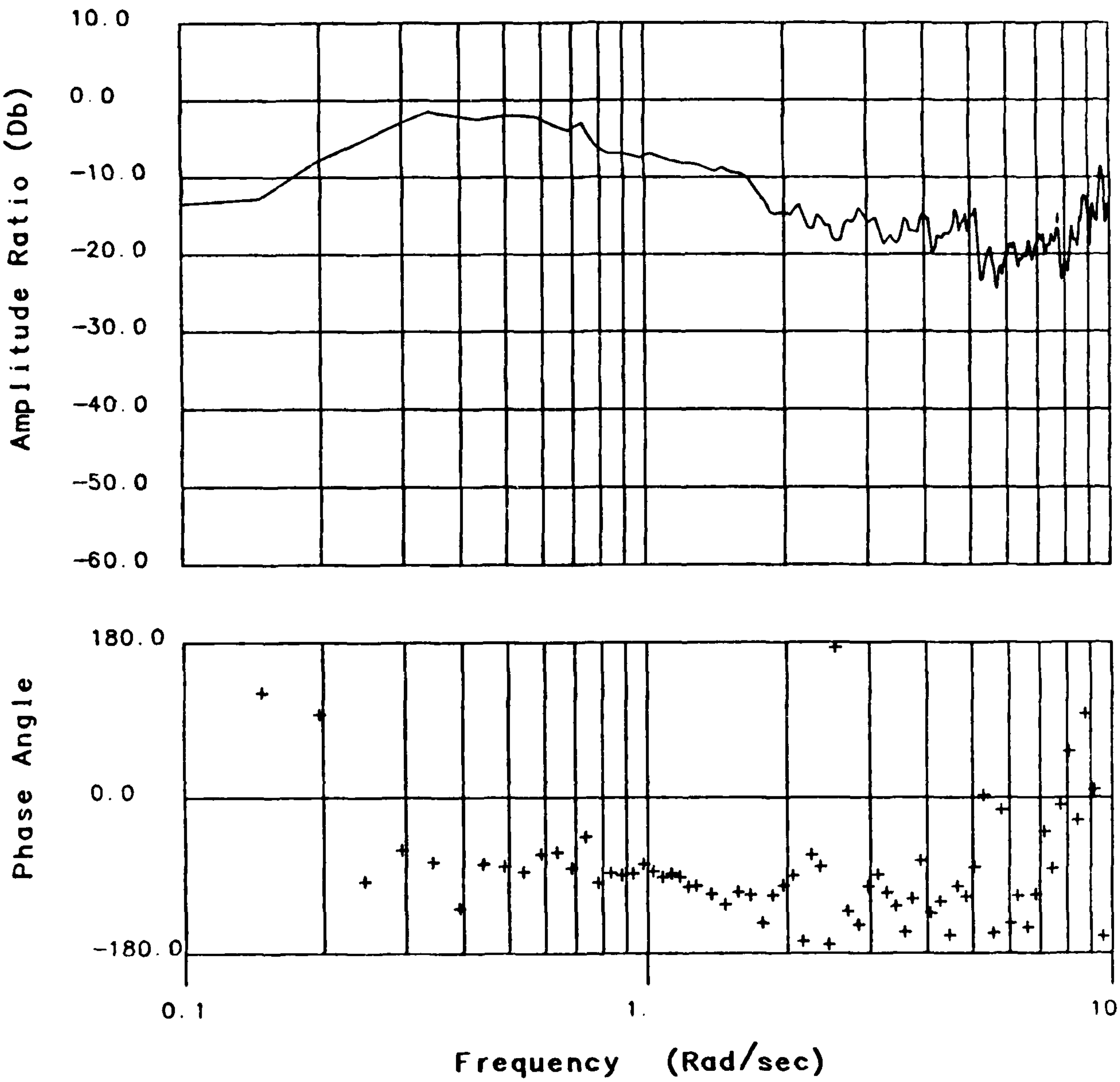


FIG. 22: BODE PLOT, VERTICAL VELOCITY/COLLECTIVE, MODEL 0
WITH Z_w = -0.05 sec^{-1}

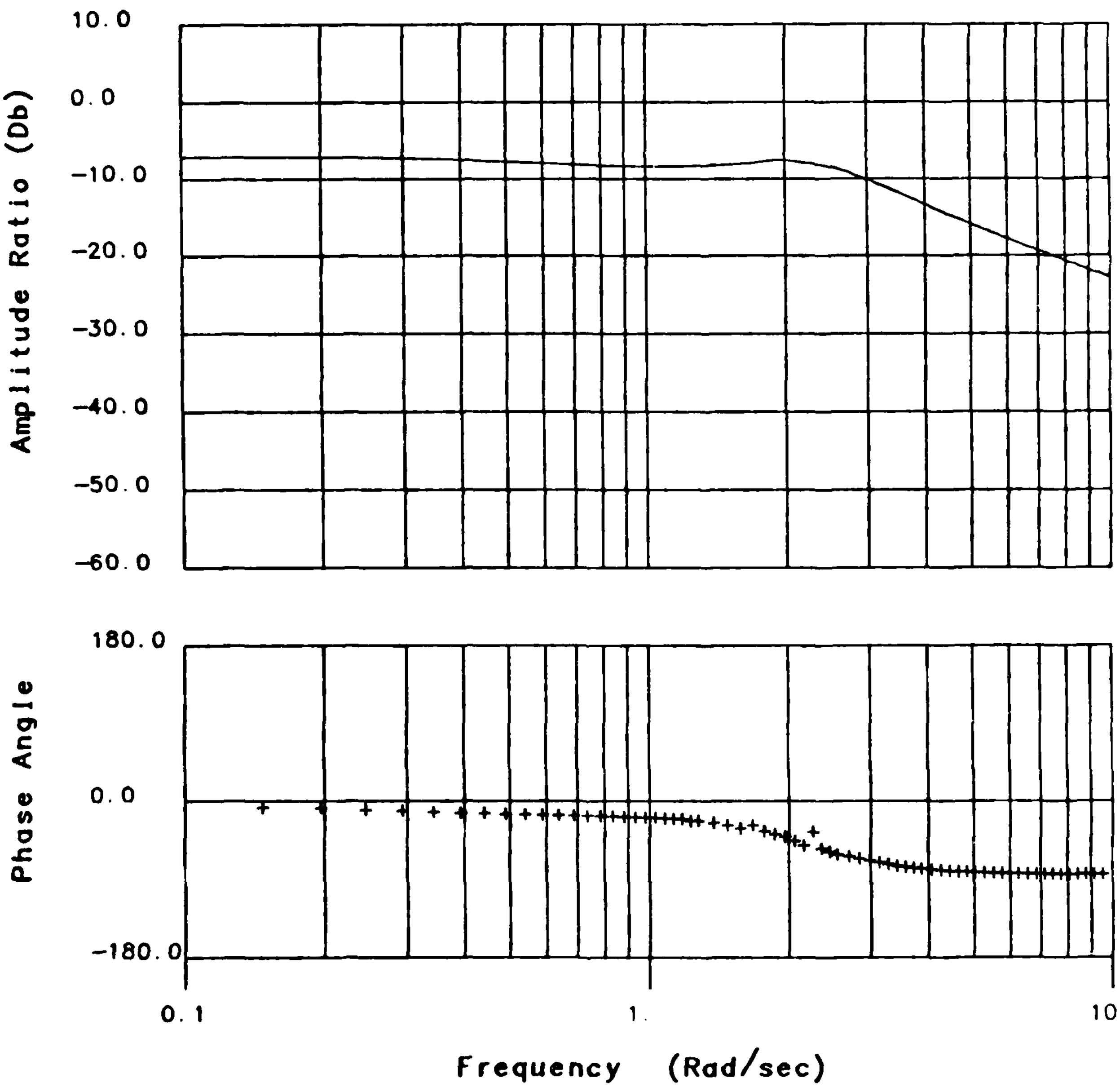


FIG. 23: BODE PLOT, TORQUE/COLLECTIVE, MODEL 0

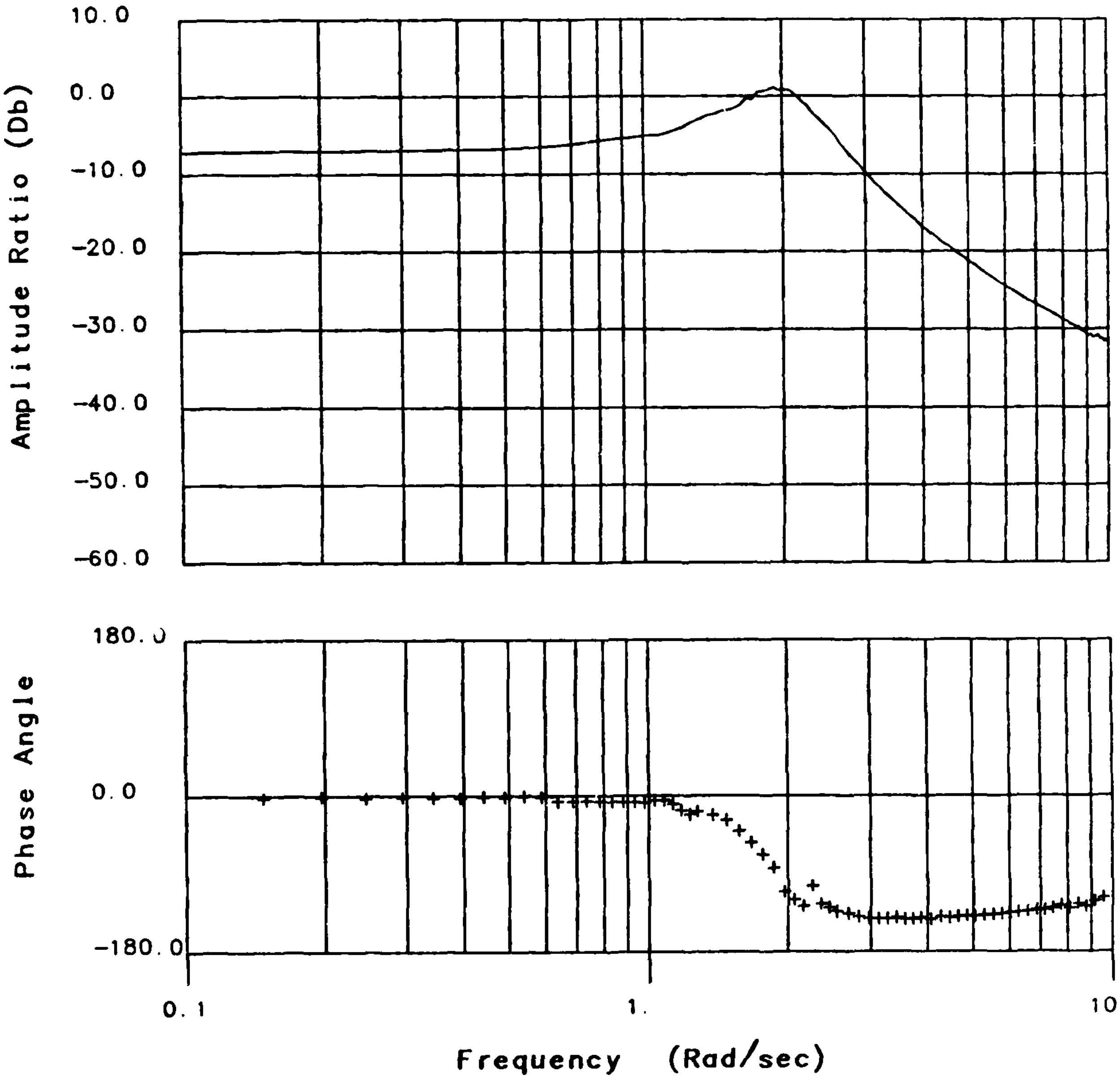


FIG. 24: BODE PLOT, TORQUE/COLLECTIVE,MODEL 1

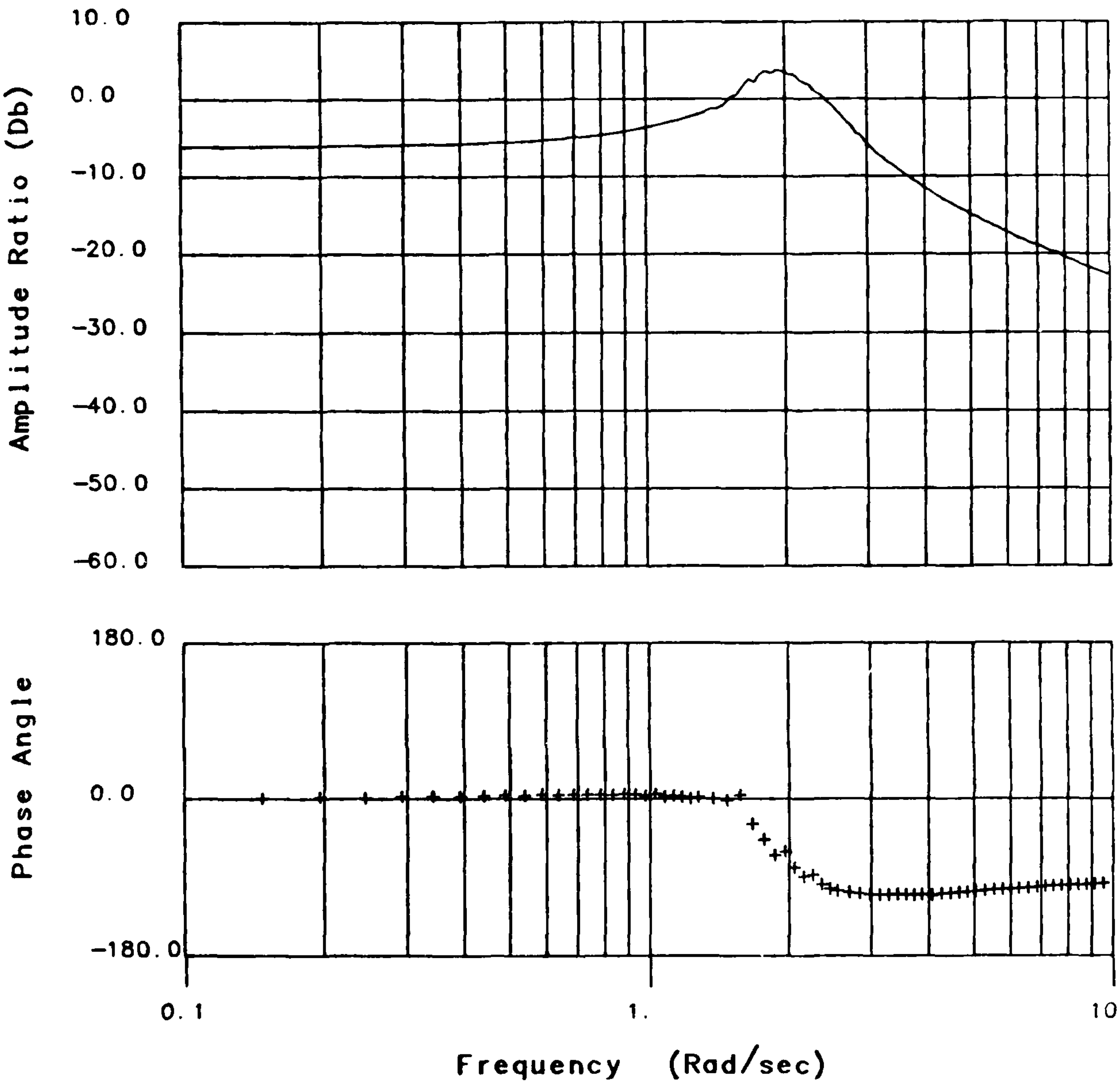


FIG. 25: BODE PLOT, TORQUE/COLLECTIVE, MODEL 2

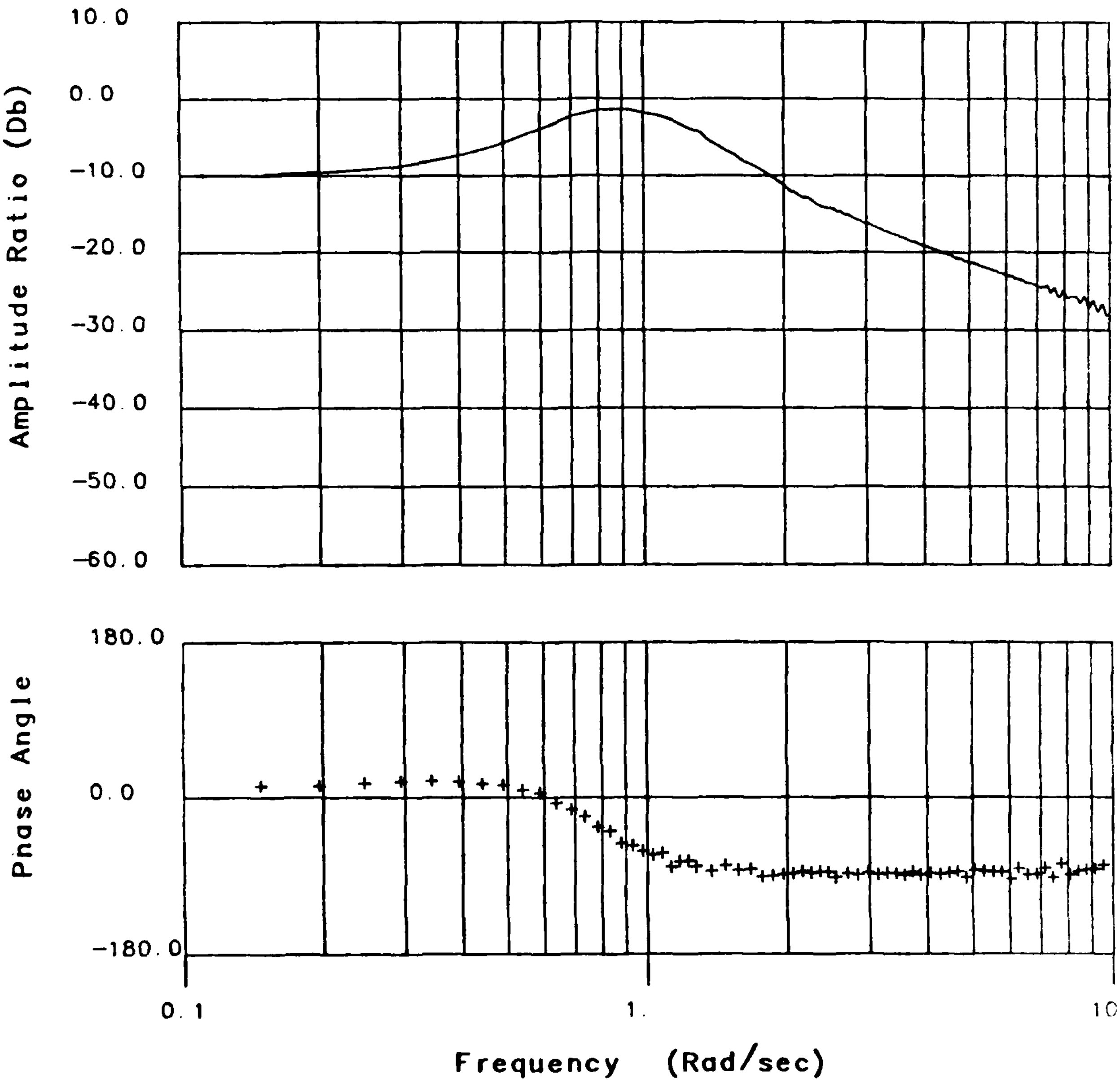


FIG. 26: BODE PLOT, TORQUE/COLLECTIVE,MODEL 4

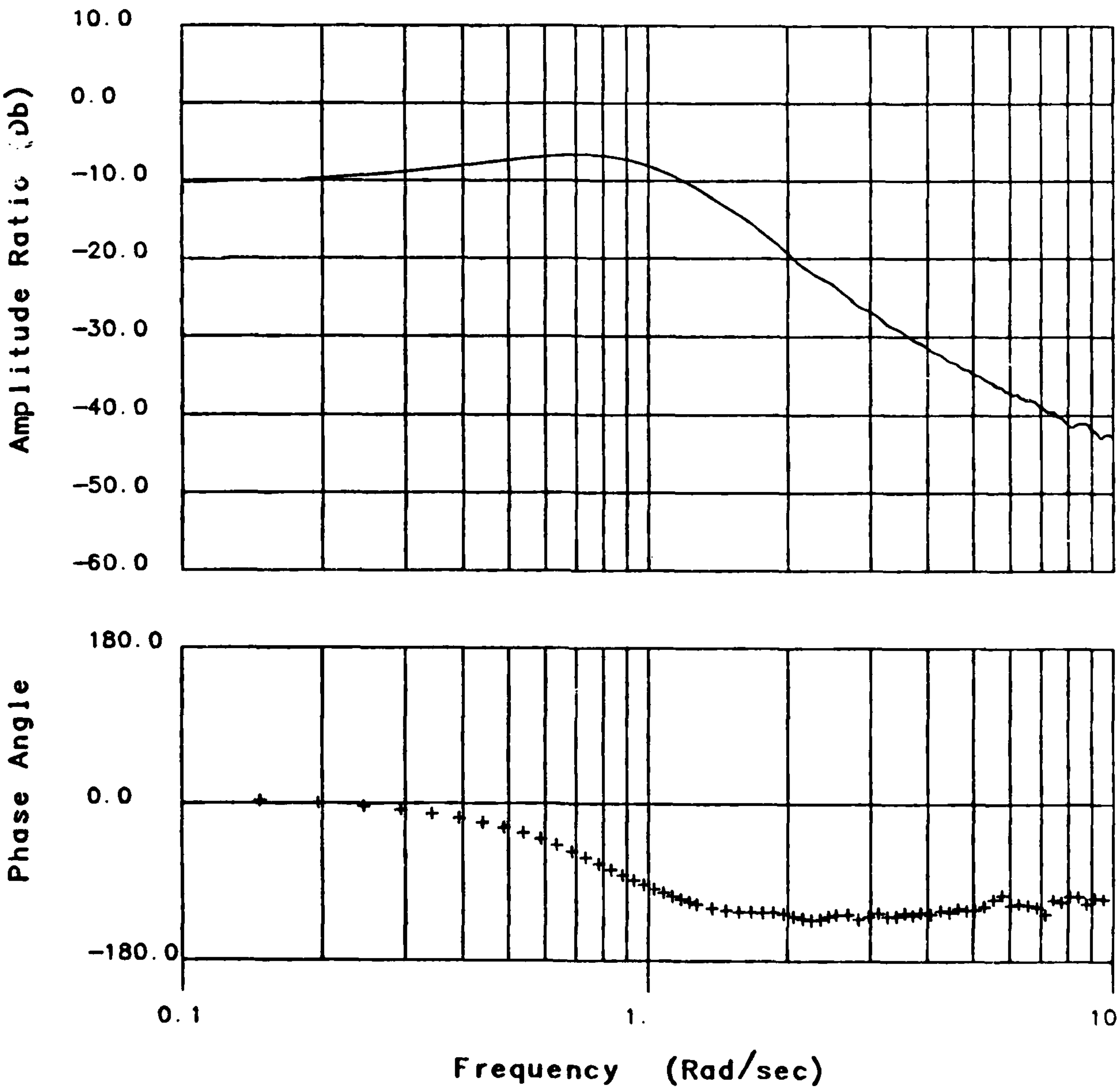


FIG. 27: BODE PLOT, TORQUE/COLLECTIVE, MODEL 6

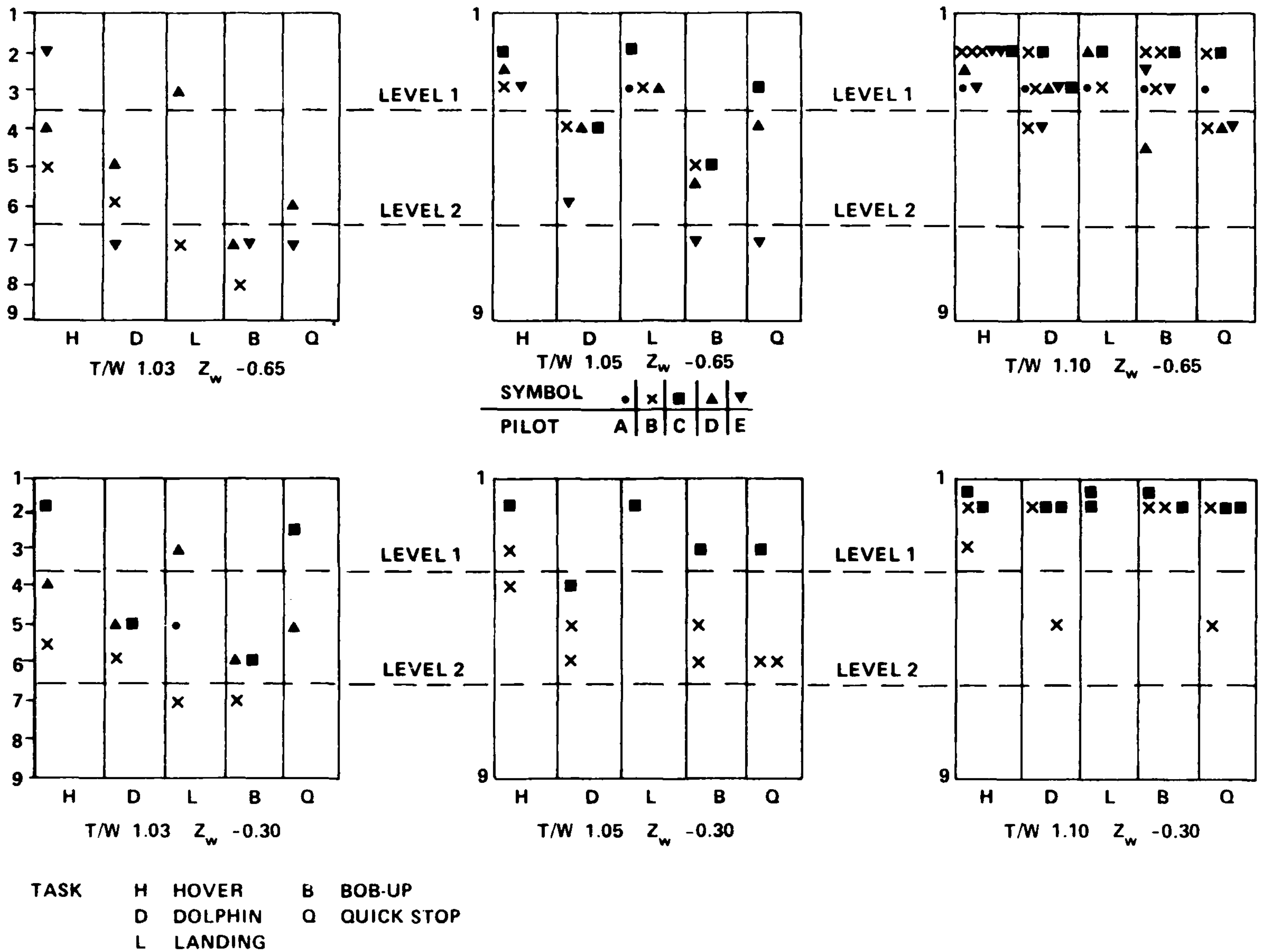


FIG. 28: T/W - Z_W HANDLING QUALITIES RATINGS

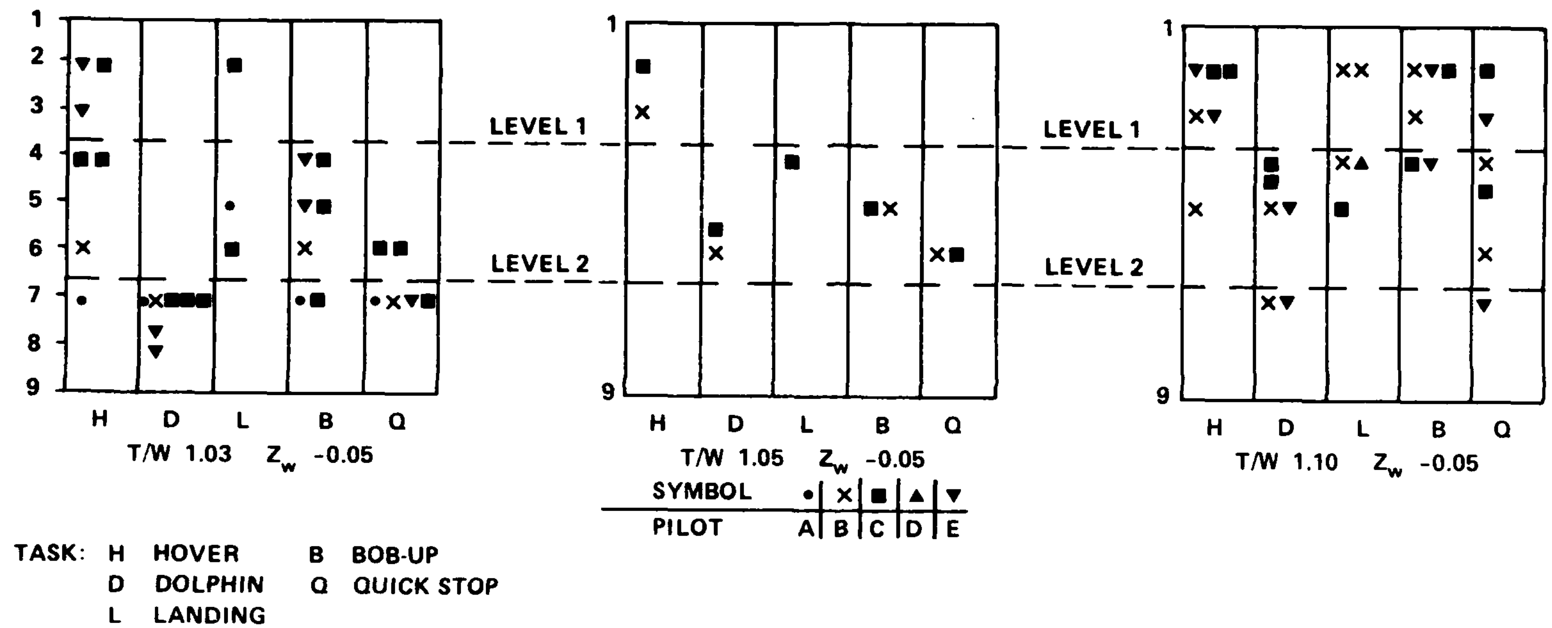


FIG. 28: T/W — Z_W HANDLING QUALITIES RATINGS (Cont'd)

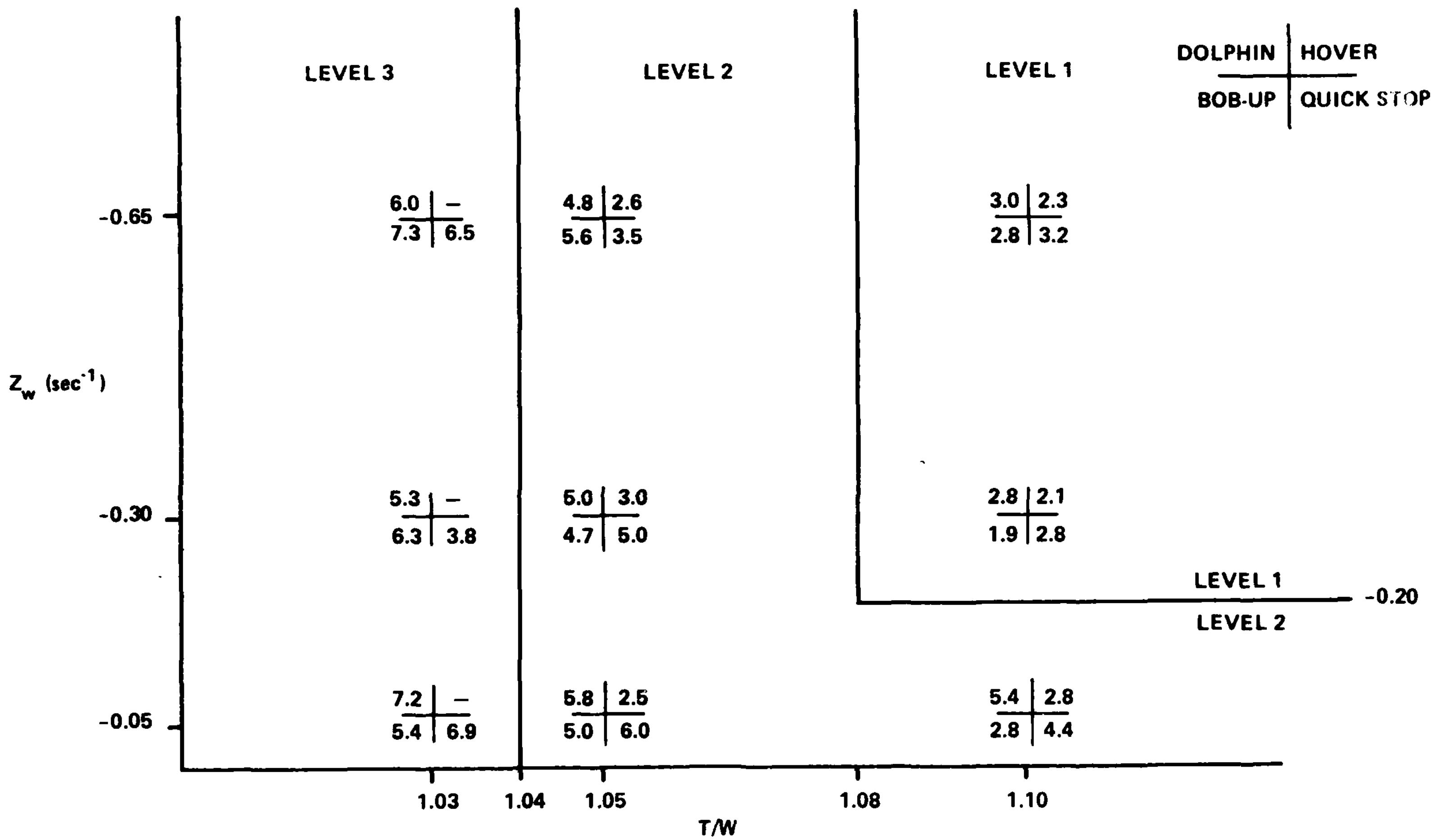


FIG. 29: T/W, Z_W HANDLING QUALITIES LIMITS

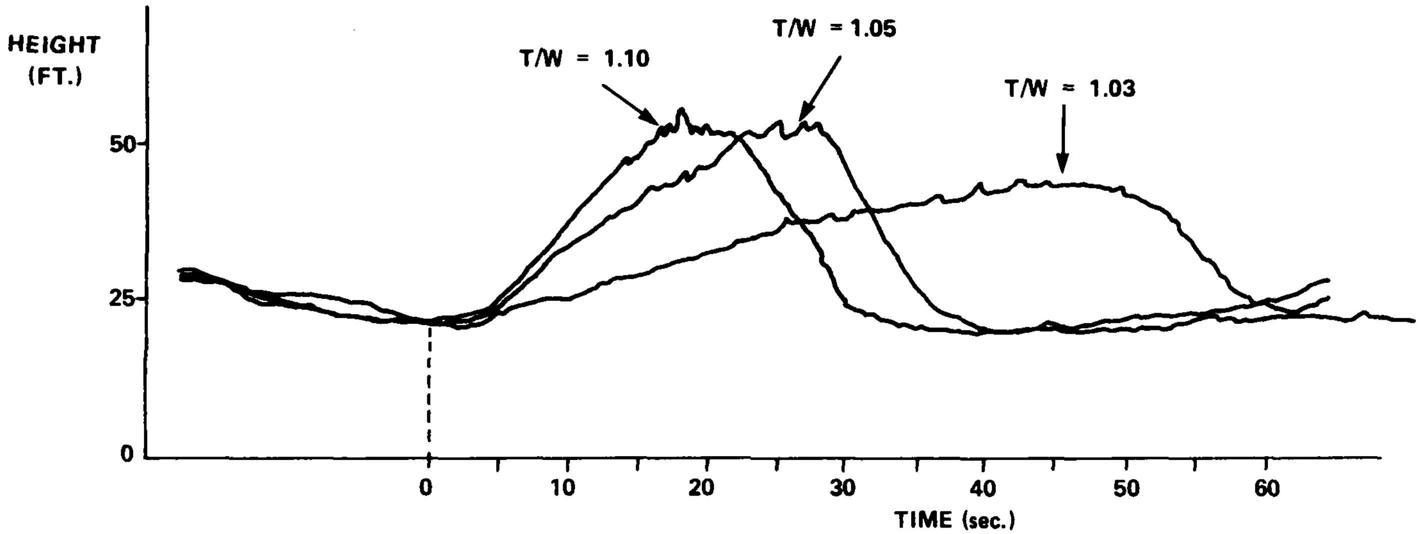


FIG. 30: EFFECT OF T/W ON BOB-UP PERFORMANCE

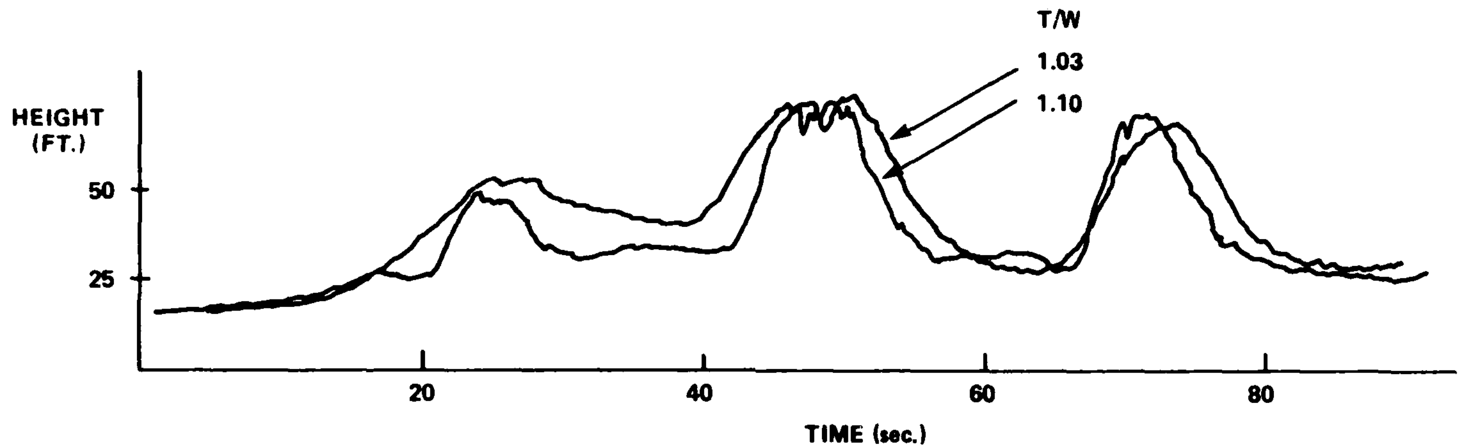


FIG. 31: EFFECT OF T/W ON DOLPHIN TASK FLIGHT PATH

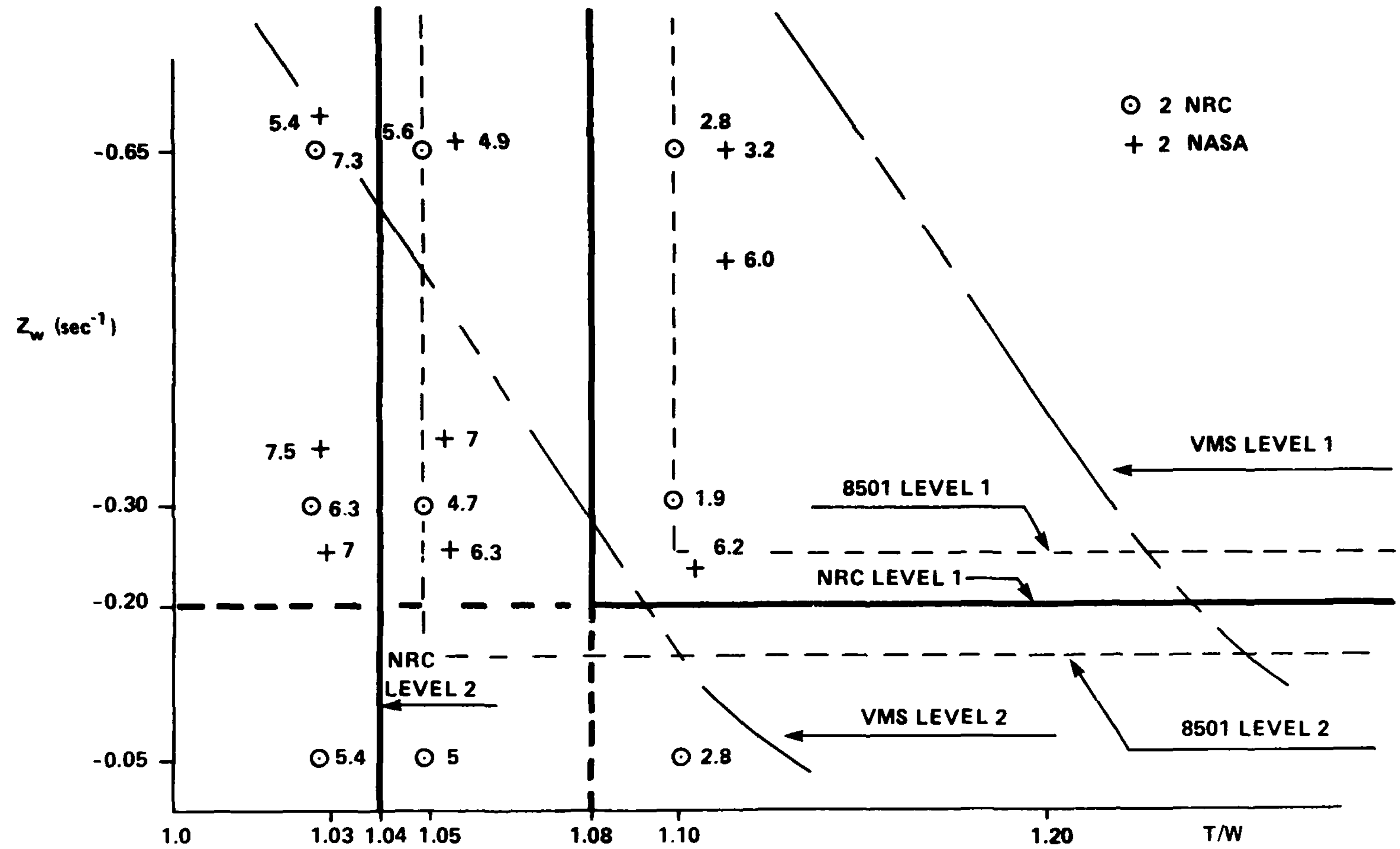


FIG. 32: T/W - Z_W ENVELOPES – BOB-UP TASK ALONE

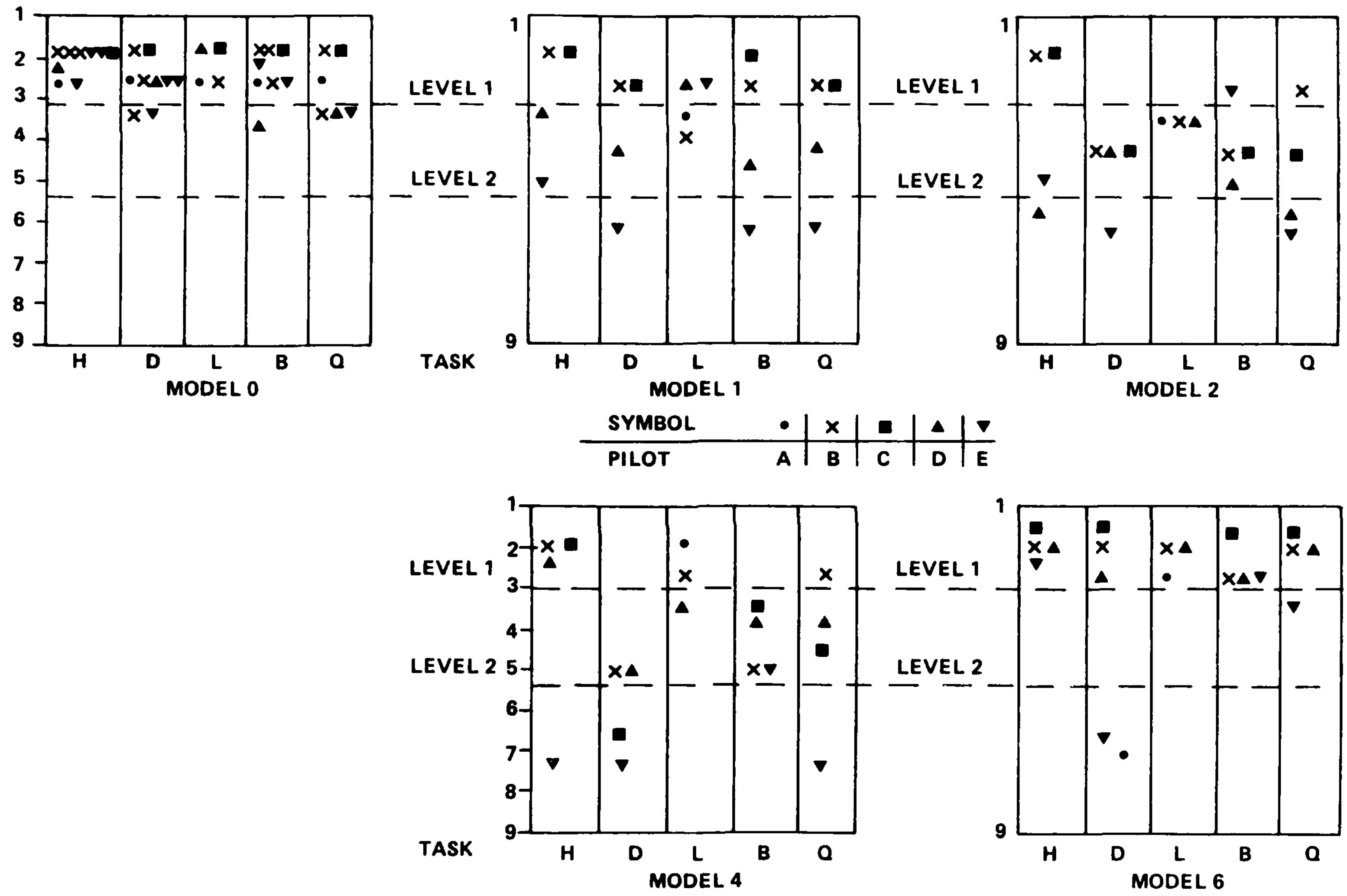


FIG. 33: ENGINE-ROTOR MODEL HANDLING QUALITIES RATINGS

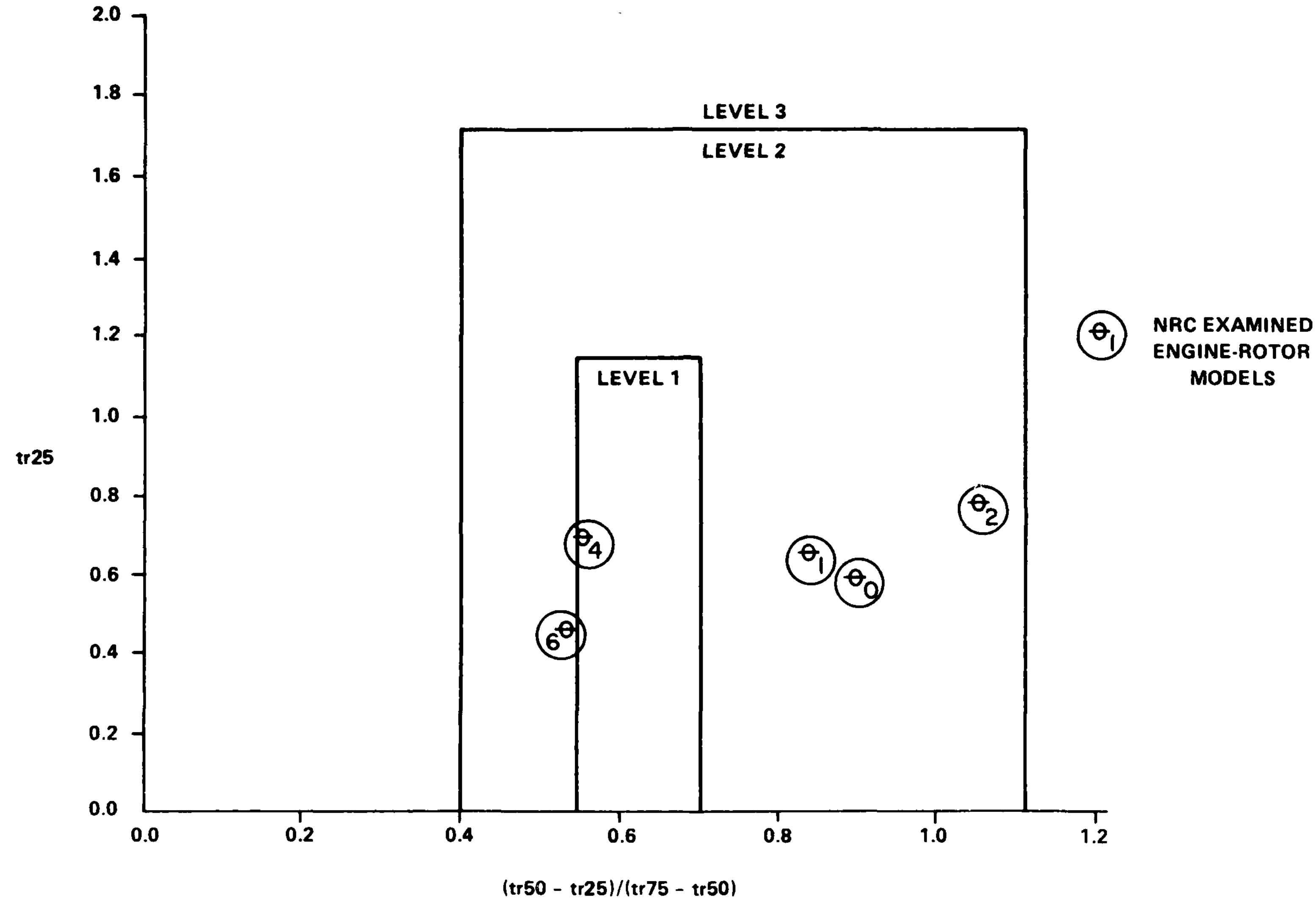


FIG. 34: VERTICAL VELOCITY SHAPING PARAMETER ENVELOPE

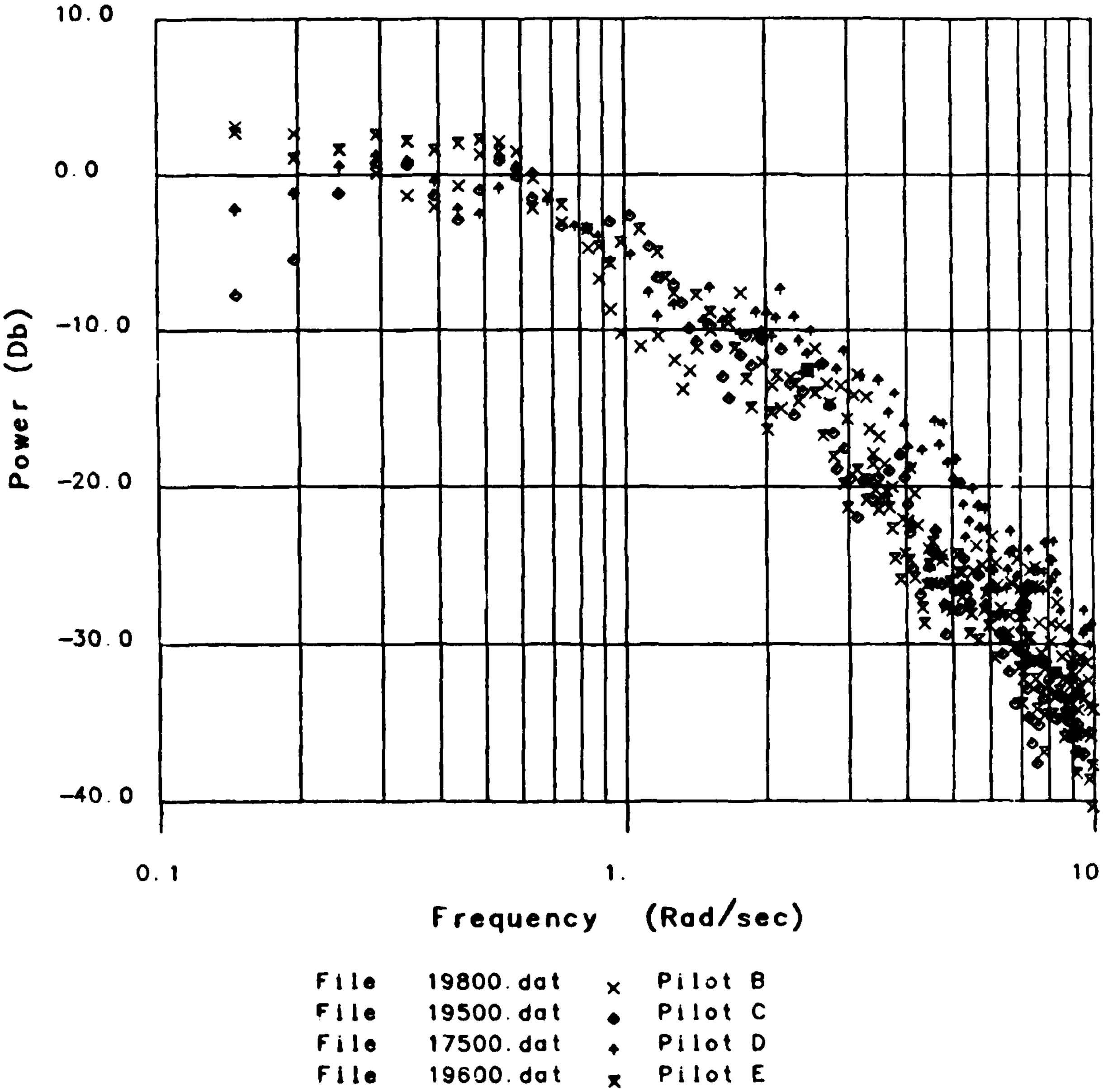


FIG. 35: PILOT FREQUENCY CONTENT, MODEL 0, COLLECTIVE CONTROL

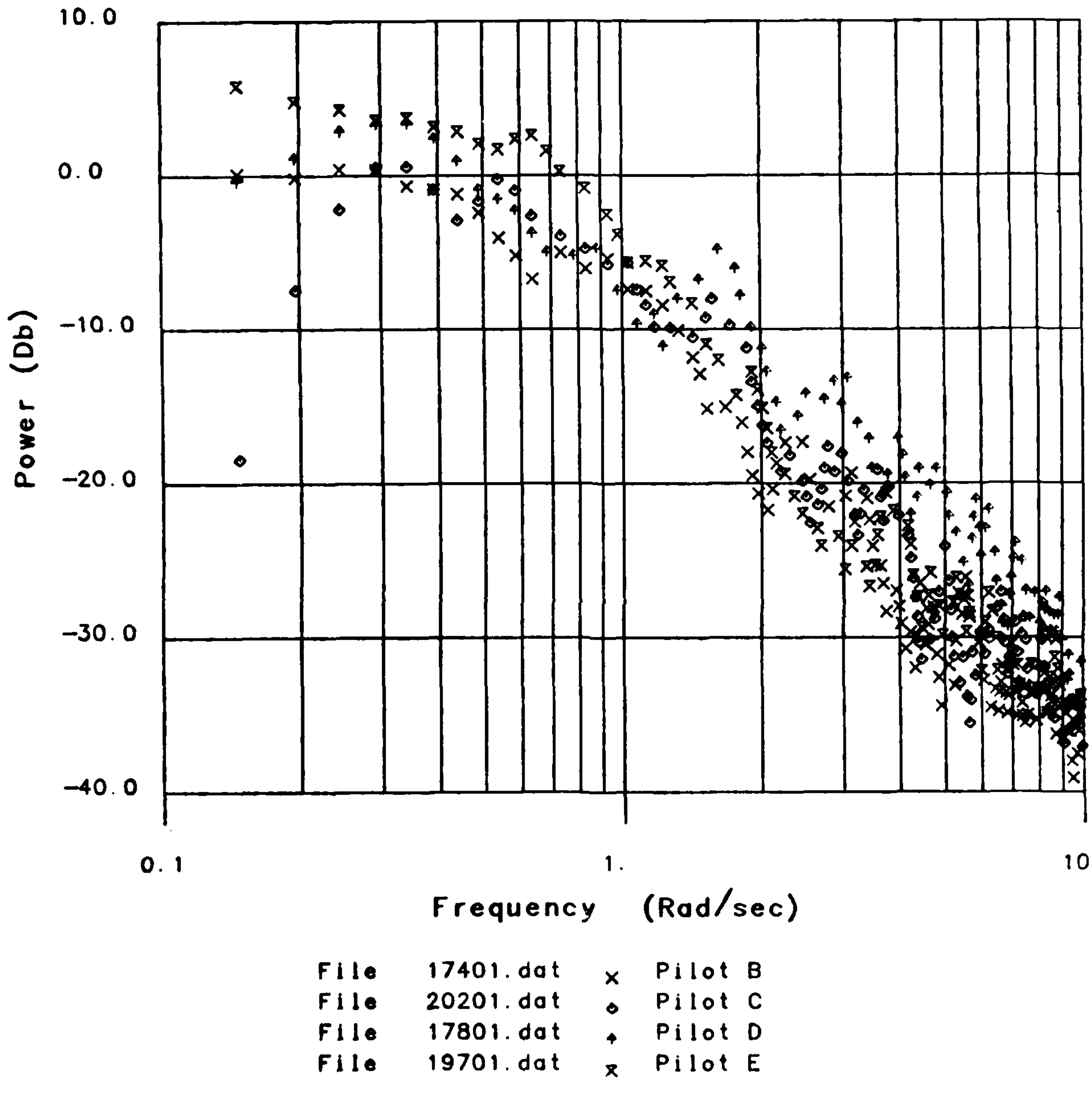


FIG. 36: PILOT FREQUENCY CONTENT, MODEL 1,
COLLECTIVE CONTROL

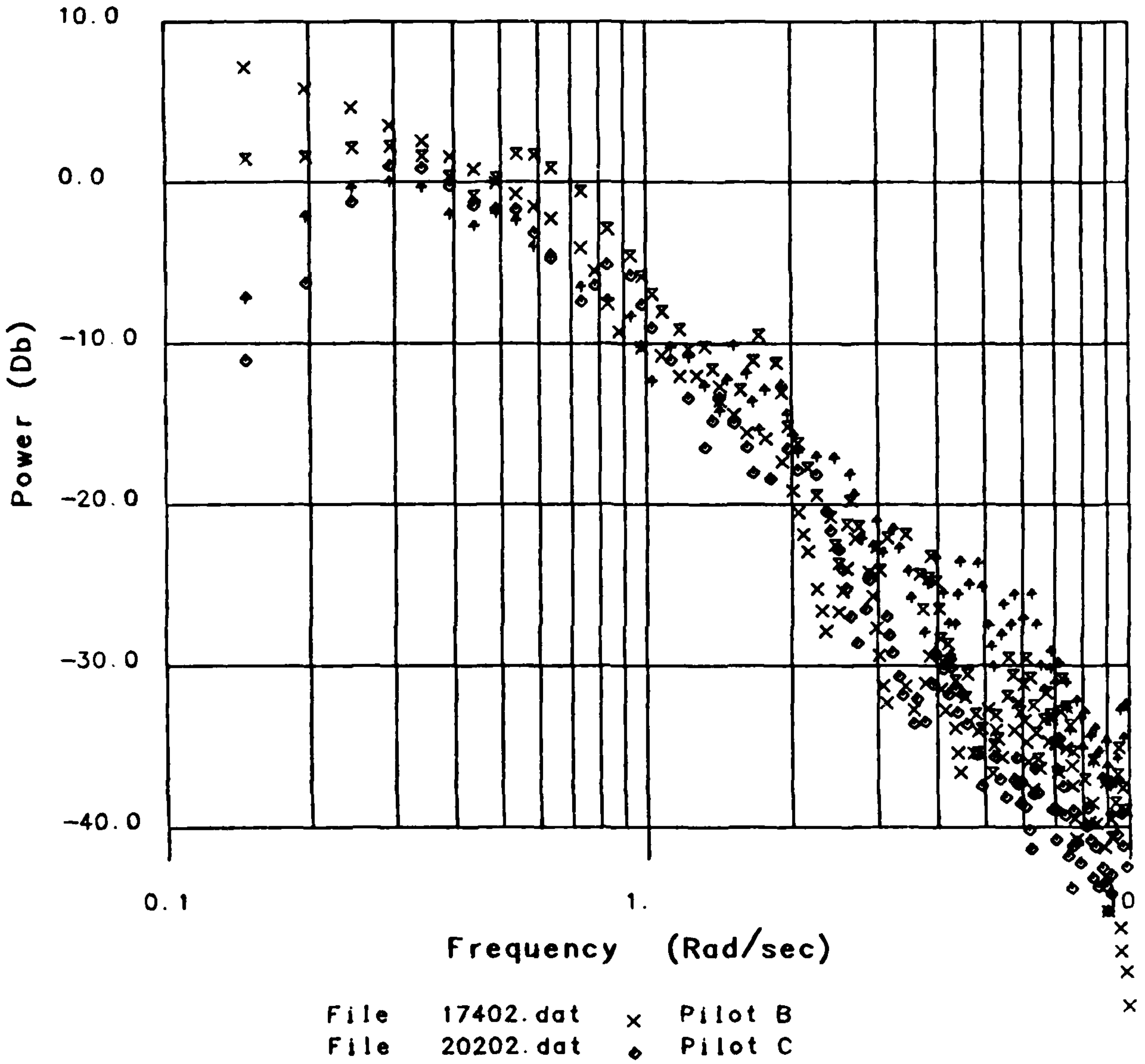


FIG. 37: PILOT FREQUENCY CONTENT, MODEL 2, COLLECTIVE CONTROL

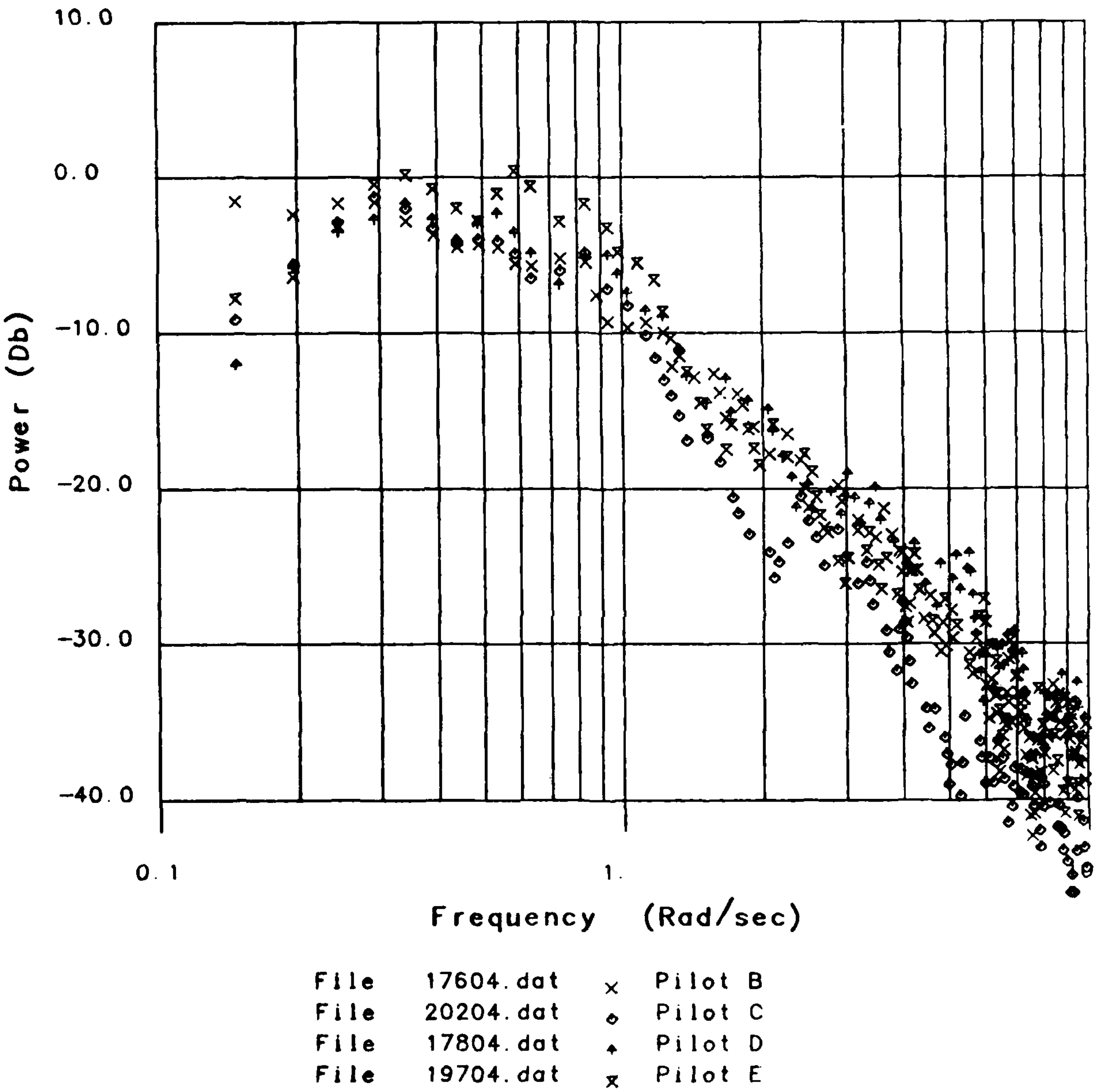


FIG. 38: PILOT FREQUENCY CONTENT, MODEL 4, COLLECTIVE CONTROL

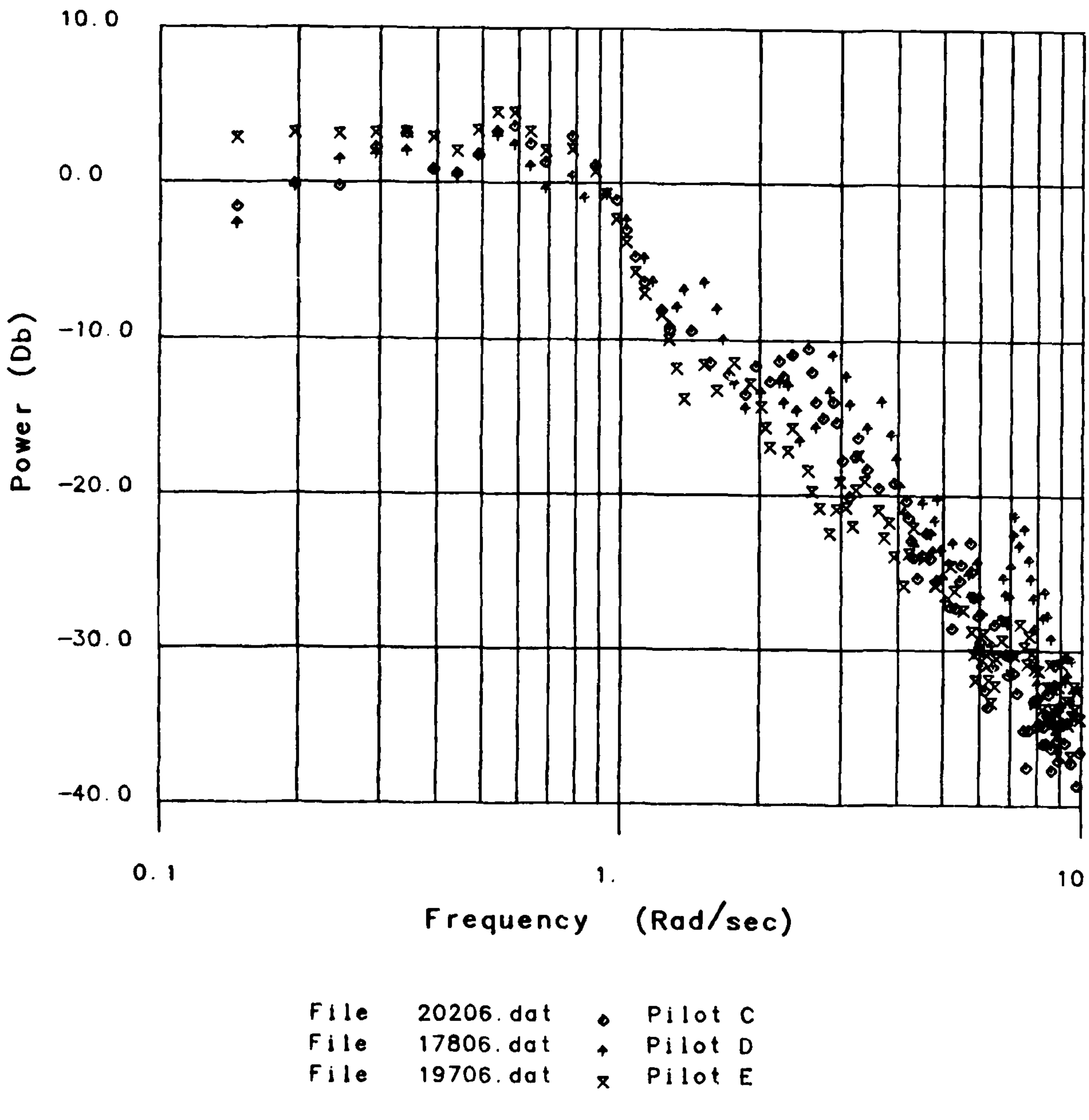


FIG. 39: PILOT FREQUENCY CONTENT, MODEL 6,
COLLECTIVE CONTROL

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4

AUTHOR(S)/AUTEUR(S)

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9	10	11	12a	12b

NOTES

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DESCRIPTORS (KEY WORDS)/MOTS-CLÉS

1. Helicopter control
2. Helicopters - aerodynamic characteristics
3. Helicopters - control systems
4. Vertical axis handling qualities

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SUMMARY/SOMMAIRE

The results of two in-flight simulation programs on the impact of vertical axis characteristics on rotorcraft handling qualities are presented. The parameters investigated in these studies were heave damping, thrust to weight ratio, and various dynamic response characteristics of the combined engine, governor and rotor system. Flight tasks included hover, hover manoeuvring and nap of the earth flight. Evaluation of 11 configurations where heave damping and thrust to weight ratio values were varied provides the basis to suggest that the amount of heave damping represented by $Z_w = -0.20\ sec^{-1}$ and a thrust to weight ratio of 1.08 are the boundary values for Level 1 helicopter handling qualities. These results are compared with other relevant work on the topic.

Stabilization and control of engine torque was found to be a major source of pilot workload for models with higher order engine-rotor system response characteristics of a 3 db resonant peak in the transfer function between collective and engine torque is postulated as an upper limit for Level 1 handling qualities. The benefit of displacing this peak to higher frequencies, corresponding to separating the resonance from the typical pilot's bandwidth, is suggested. The evaluation results tend to discount the use of a vertical velocity shaping parameter for definition of Level 1 attributes when thrust to weight ratio is a dominant factor and suggest that the impact of such dynamic characteristics is highly sensitive to pilot technique and adaptability.

Note: This report makes reference to a proposed revision to MIL-H-8501A (Reference 5) which was published December 1985. Subsequent editions of the proposed revision incorporate many of the conclusions detailed in this report.

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MARCH, 1988
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